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Deltas, dunes and playas: the evolution of a Lake Frome embayment from the late Quaternary to the present day

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Deltas, dunes and playas: the evolution of a Lake Frome embayment from the late Quaternary to the present day

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ABSTRACT

The response of the Australian landscape to future climate change can be gauged by studying the effects that climatic change has had on environments in the past. The timing, extent and synchronicity of the lacustrine and playa periods which were experienced in the north and south of the Australian continent during the Quaternary are still not well understood. A detailed understanding of the climate drivers and the response of the Australian landscape at this time to climatic variables would not only help us to plan for future climate change it would also help to answer key questions such as the reasons for megafaunal extinction and the extent to which the first humans in Australia modified this environment.

Lake Frome is a playa lake located in the south of the Lake Eyre Basin in South Australia. A study site was identified along the western shoreline of the playa lake which is dissected by ephemeral streams that rise in the Flinders Ranges and characterised by a large number of what appear to be bank attached spits. This study demonstrates that playa shoreline features which appear to be beach ridges are actually relict fluvio deltaic units. A combination of thermoluminescence, accelerator mass spectrometer ^{14}C and amino acid racemisation ages provide bounding timeframes for the investigation of two such fluvio-deltaic features and adjacent lake floor facies and aeolian landforms. The ages are combined with a study into the stratigraphy and microfossil ecologies at the site and reveal a mega high lake stage at around 110-100 ka and two major periods of high volume runoff from the Flinders Ranges between 92-80 ka and 17-11 ka during which lake levels were at a minimum elevation of 4-6m (AHD). Following this a transition to ephemeral conditions was experienced at this site between 7-6 ka which continues today. In addition to the palaeoenvironmental reconstruction of the site amino acid racemisation was carried out on ostracod valves from the lake floor to assess the viability of such dating methods for playa lakes. This study found that pre-treatment with bleach (NaOCl) was useful in correcting slight reversing trends caused by a combination of environmental factors and with further work to gain a better understanding of such processes could become a valuable tool for age determination in such environments.

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Chapter 1: Introduction

1.1 Context of Thesis

A number of different palaeoenvironmental studies have been carried out on the lake floor sediments from Lake Frome. These reports have returned fairly consistent findings proving the validity of such studies despite the fact that they have been carried out on the same two sets of cores and several discrepancies which have been found in relation to the radiocarbon ages. These studies whilst valuable indicators of the lake environment also lack the ability to provide information on the depth of water in the lacustrine periods and the weather systems that might be responsible for runoff at the time. Australia has many but there are still gaps in our knowledge about what mechanisms drive climatic changes and how the natural environment of the Australian continent has responded to climatic variation. This thesis provides a detailed multi-proxy analysis of playa lake facies at one site along the perimeter of Lake Frome in South Australia and an interpretation of how the response of this landscape fits into what we know about regional climatic change during the Mid to Late Quaternary.

1.2 Lakes as palaeoenvironmental indicators

Lake basins are valuable records of past environments and often hold particularly comprehensive information on basin wide hydrology and climatic changes that have been experienced during the Quaternary (Singh 1981; Bowler *et al*. 1986; Machlus *et al.* 2000; Schofield *et al*. 2004; Burrough & Thomas 2009). Palaeoenvironmental reconstructions using lake sediments have often been divided between paleaolimnology where research is based on the information obtained from the environment of the lake floor sediments, and geomorphology in which investigations are based on the morphology of shoreline formations. Increasingly though it is being recognised that by combining the two methods a superior multi-proxy picture of climatic related changes with can be constructed which encompasses the lake environment as described in the lake floor sediments and lake levels and fluctuations as described in beach and deltaic formations (Machlus et al. 2000; Schofield *et al*.

2004; Burrough & Thomas 2009). In addition the combination of methods allows for gaps within records to be minimised, whereby information from one environment may explain or fill in for the lack of information in the other, in either the sedimentary record or with regard to datable materials and methods. Much work has been carried out in Australia on the shorelines by and lake floor sediments of our playa lakes but we still lack an understanding of the stratigraphic and geochronological relationships that exist between lake floor and shoreline features.

1.3 Aims and objectives

There are currently gaps in the current literature with regard to stratigraphic, chronological and palaeoenvironmental relationships that occur between lake margin and lake floor features. This thesis aims to fill these gaps by assembling a detailed environmental reconstruction of an arid zone playa lake. In order to do this there are three main aims of this thesis:

1. To describe, correlate and interpret the stratigraphy of adjacent lacustrine, fluvio deltaic and aeolian features of an arid zone playa lake.

2. To examine the palaeoenvironmental characteristics of a playa floor through analysis of microfossil assemblages and asses the usefulness of ostracod fossils in the playa environment as geochronological indicators.

3. To compare the results of this research project with the existing literature in order to construct a detailed chronology of hydrological and palaeoclimatic events and climatic conditions in Southern Central Australia during the late Quaternary.

   In conclusion the findings from this study will be used in conjunction with the existing literature to provide a study of climatic changes during the late Quaternary/Holocene in arid central Australia.

Chapter 2: The Lake Frome basin regional setting

2.1 Introduction

This chapter provides a general description of the physiography, climate and hydrology of the Lake Eyre Basin and a more detailed account of the Lake Frome sub-basin area. Lake Frome is one of five playa lakes located within Australia's largest drainage basin the Lake Eyre Basin (Figure 2.1). The Lake Eyre basin covers an area of 1.3 $km^2 \times 10^6$ and drains a substantial portion of the Australia continent (Magee et al. 1995; Nanson et al. 1998). The basin is marked by highly variable rainfall and low relief and contains five major playa lakes running roughly north to south along the fault lines of the underlying geology. Lake Frome occupies the most southerly aspect of the basin just east of the Flinders Ranges where a number of ephemeral creeks rising in the ranges currently supply intermittent runoff via the western margins of the lake.

2.2 Lake Frome geographical Setting

Lake Frome is an ephemeral salt lake or playa located at latitude of 30 - 31° south and is the most southerly playa in an arc of ephemeral lake bodies that lie to the southeast of Lake Eyre in the Lake Eyre Basin (Figure 2.2). The Lake Eyre basin occupies a structural depression in the centre of Australia and drains an area of approximately 1.3 million km^2, where rainfall and runoff range from highly variable to very low (Magee *et al.* 1995; Alley 1998). At just under a third of the size of Lake Eyre, Lake Frome is the largest of the south-eastern lakes covering an area of approximately 2,700 km^2 at an average elevation close to sea level only falling to 2 metres below sea level at the lowest points (Bowler *et al.* 1986; Nanson *et al.* 1998). It is bordered by the Flinders Ranges in the west, by the Strzelecki desert in the east and Lake Callabonna to the north (Draper & Jensen 1976; Bowler *et al*. 1986; Figure 2.2).

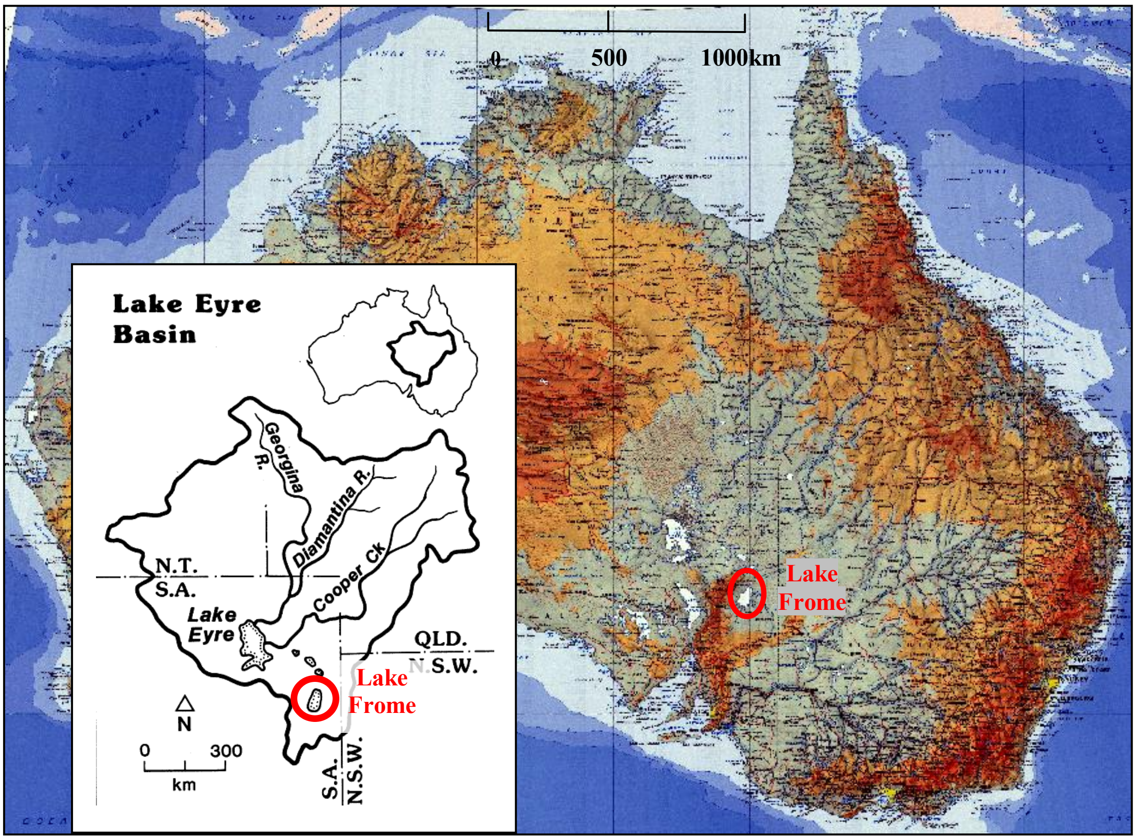

Figure 2.1: Location of Lake Frome a) in Australia and b) within the Lake Eyre Basin. (Geoscience Australia 1:5M scale mosaic; Lake Eyre Basin map modified after Nanson *et al.* 1998).

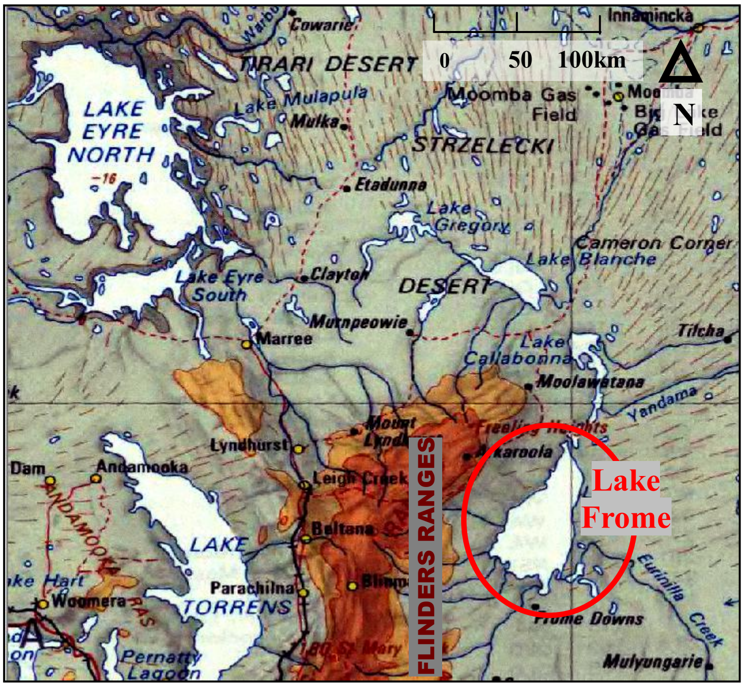

Figure 2.2: Lake Frome the most southerly lake in the Lake Eyre Basin. (Modified after Geoscience Australia 1:5M scale mosaic).

2.3 Lake Frome geological Setting

Mesozoic geology

The Lake Eyre basin lies across the south western extension of the Jurassic-Cretaceous sand stone units of the Great Artesian Basin (Wopfner *et al*. 1974; De Deckker *et al*. 2011). Great Artesian Basin sediments underlying Lake Frome include an unnamed Jurassic conglomerate, the predominately marine upper Cadna-owie Formation and the Cretaceous siltstones of the Maree Subgroup (Callen 1981; Sheard 2009). A number of fault lines exist in the Great Artesian Basin sandstones that lie beneath the Lake Frome basin and as a result leakage from the Great Artesian Basin aquifers can contribute to both ground and surface water at Lake Frome (Ullman & Collerson 1994; De Deckker *et al*. 2011).

Cenozoic geology

The Eyre Formation lies unconformably above the Great Artesian Basin sandstones and marks the onset of the subsidence that formed the Lake Eyre Basin (Wopfner *et al*. 1974). Deposition of the Lake Eyre Formation began as the internal drainage basin was forming in the middle of the continent from the Late Paleocene to the Mid Eocene (Alley 1998). The basin formed due to intracratonic subsidence as the Olary and Barrier Ranges rose to the south and to the east, and braided rivers extending across the breadth of the basin deposited the Eyre Formation which consists of polished well rounded gravel and quartz sands in units up to 100m thick (Wopfner *et al*. 1974; Callen & Tedford 1976; Alley 1998).

Although only scarcely represented in the Frome region silcrete was formed extensively across the Lake Eyre Basin during the Ogliocene as a result of weathering and pedogenic alteration or by groundwater silicification (Callen 1981; Callen 1983; Alley 1998).

During the Late Oligocene to the Early Miocene a series of anticlines rose across the Lake Eyre Basin to form the Cooryanna, Gason and Kopperamanna Domes (Wopfner 1974; Callen & Tedford 1976; Alley 1998; Sheard 2009). The rise of the anticlinal domes resulted in the separation of the Lake Eyre Basin into a northern and a southern sub basin which today are called the Tirari and the Callabonna sub-basins (Figure 2.3). Following compartmentalisation of the Lake Eyre Basin the Namba Formation was deposited in the Callabonna-Frome sub basin during the Miocene and it lies disconformably over the Eyre Formation in units around 150 metres thick (Callen & Tedford 1976; Alley 1998). In the Lake Eyre region the Etadunna Formation was deposited contemporaneously to that of the Namba Formation. Both the Namba and the Ettadunna Formations consist of fine to medium sands, silt, clay, oolitic dolomite and limestomes which were deposited in expansive, shallow lake-like conditions in a warm environment (Callen & Tedford 1976; Alley 1998).

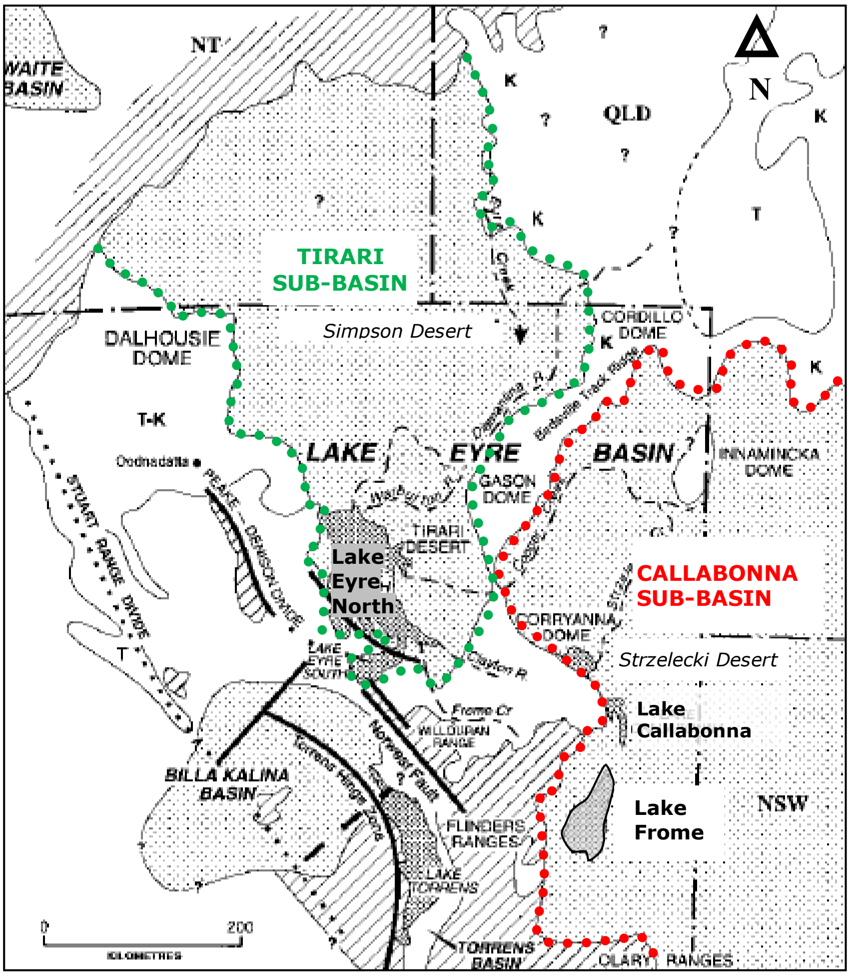

Figure 2.3: Compartmentalisation of the Lake Frome Basin into the Tirari sub-basin in the north and the Callabonna sub-basin where Lake Frome is located in the south. (Modified after Alley 1998).

Silcrete and ferricrete development across the whole Lake Eyre basin occurred again during the Late Miocene to Early Pliocene as the environment dried and sediments were once again modified by groundwater movements (Callen & Tedford 1976; Alley 1998).

Although there is uncertainty about the exact timing of the initial uplift of the Flinders Rangers it is thought to have taken place no earlier than the Cenozoic as fluvial sediments from the Early Cretaceous make up the capping sediments of various ridge tops within the ranges (Wellman & Greenhalgh 1988; Celerier *et al.* 2005). The uplift of the Flinders Ranges is thought to have resulted in the deposition of the Willawortina Formation at Lake Frome in the Late Pliocene/Early Pleistocene (Callen & Tedford 1976; Alley 1998). The Willawortina Formation which consists of alluvial fan gravel and mud flow sediments and lies above the Namba formation in the form of a westward thickening discontinuous wedge at the western margin of the Lake Frome basin (Figure 2.4).

Following the deposition of the Willawartina Formation, the Millyera Formation was deposited unconformably over the Namba Formation across the eastern floor and shore of Lake Frome (Figure 2.4). The Pleistocene Millyera Formation consists of units up to 10m thick which are formed of laminated clays, limestone and sand representing lacustrine deposition in the Lake Frome Basin (Callen & Tedford 1976). High stand sandy beach ridge facies were also deposited during the Pleistocene lacustrine events (Alley 1998). These beach ridge facies, named the Coomb Spring Formation intertongue with the Millyera Formation to the east of Lake Frome, and represent deposition of the coarser sediments at high lake levels (Figure 2.4)

The Late Pleistocene Eurinilla Formation consists of shoreline and channel fill structures of poorly sorted sands and clays in units up to 20m thick which were deposited along the east and the western margins of Lake Frome (Figure 2.4) and its ephemeral tributaries (Callen 1976; Callen & Tedford 1976). The Eurinilla Formation along with its equivalent the Katipiri formation around Lake Eyre, are thought to have formed from re-activated fluvial and lacustrine deposition during the

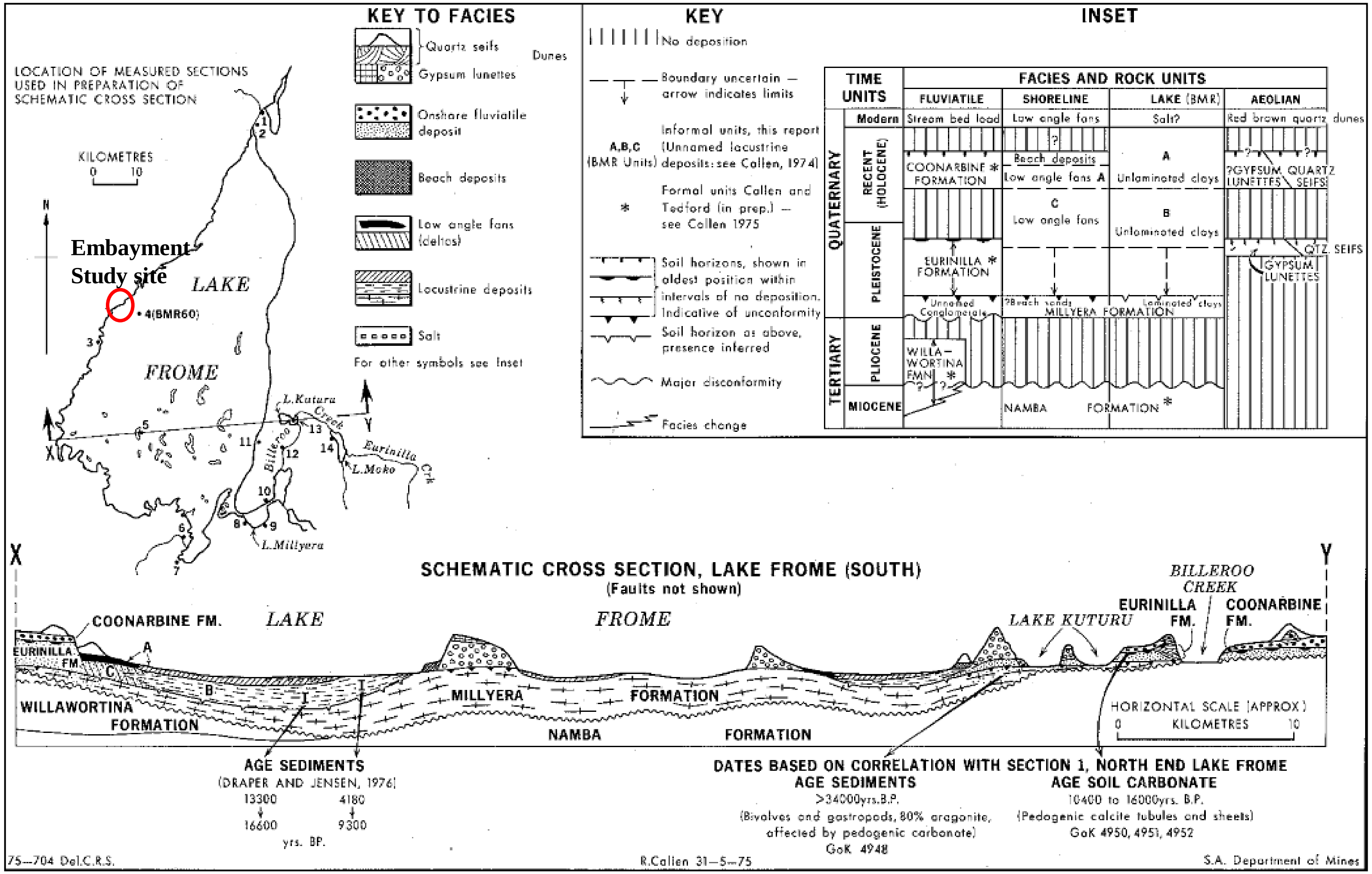

Figure 2.4: Relationships of Cenozoic formations at Lake Frome. (Modified after Callen 1976).

last interglacial MIS 5 (Alley 1998

The uppermost formation at Lake Frome is the Coonarbine Formation which lies disconformably above the shoreline sections of the Eurinilla Formation (Figure 2.4) and also forms the central facies of the modern dunes around Lake Frome and to the east in the Strzelecki desert (Callen & Tedford 1976). The Coonarbine Formation consists of poorly sorted fluvial and aeolian silt, sands and occasionally gravels deposited during the climatic fluctuations of the Late Pleistocene and Holocene (Callen & Tedford 1976; Alley 1998).

2.4 Climate and hydrology

The Lake Eyre Basin

The playa lakes of the Lake Eyre basin are located within the arid centre of the Australian continent where presently the average of annual rainfall that is received amounts to less than 200mm (Bureau of Meteorology 2005; 2009). Whilst the majority of playa lakes within the basin are linked by dry or ephemeral channels that were formed during mega lake phases in the past, the present hydrology of the playa lakes in the basin are dominated by the climatic events that occur on a local catchment scale. Local catchment domination means that volume and seasonality of runoff flowing into each lake varies with the size and location of the tributaries to each individual lake. Lake Eyre North is the largest endorheic depression within the Lake Eyre basin and its major tributaries the Macumba River, the Cooper Creek and the Diamantina River intermittently supply runoff from catchments where summer rainfalls dominate in the north and northeast of the Australian Continent (Nanson *et al*. 1998). Lake Eyre receives water relatively frequently (approximately every 8 years) as its vast catchment area which covers 1.14 million km^2 is located in the monsoonal north of the continent which is prone to high magnitude ENSO related flooding events (Nanson *et al.* 1998). However records of water in the smaller playa lakes including Lake Frome are sparse as they are fed only by the ephemeral creeks and rivers from localised catchment areas under control of geography and topography.

Many geomorphologic features of the Lake Eyre drainage basin are relics of former climatic regimes where higher precipitation and/or lower evaporative conditions allowed surface water to carve out channels and form raised shorelines around the dry to ephemeral creeks and lakes of today (Nanson *et al.* 1998; De Deckker 1983). Creeks and channels that are for the most part dry today link the southern lakes to Strzelecki Creek (a southern branch of the Cooper Creek) via Lake Blanche and link Lake Frome to Lakes Callabonna and Blanche, and also link Lake Gregory to Lake Eyre (Figure 2.5). The eroded channels between the dry salt lakes and the network of anastomosing channels in the north east which feed into the Cooper Creek, suggests that the southern lake systems have in the past received high volumes of water from the Cooper Creek drainage system. Under present climatic conditions where reduced runoff and aridity prevail, the hydrology of the Lake Eyre Basin is for the most part segmented and whilst water from the Cooper Creek flowed into Lakes Gregory, Blanche and Callabonna during the 1974 floods it failed to reach Lake Frome (Nanson *et al.* 1998; De Deckker *et al.* 2011).

The Lake Frome basin

Lake Frome is located close to the boundary between winter (westerlies and cold front related) and summer (monsoonal & ENSO) maxima rainfall on the Australian Continent (Draper & Jensen 1976; Singh 1981; Cohen *et al.* In press). Total rainfall at Lake Frome averages around 180mm per year and it falls sporadically but mainly during the winter months whilst pan evaporation in the Lake Frome region can reach 2400mm per year (Singh & Luly 1991; Nanson *et al.* 1998; Bureau of Meteorology 2008). Minimum and maximum temperatures fall between 4.5°C and 36°C at Lake Frome (Bureau of Meteorology 2011). The prevailing winds in the Lake Frome region are southerly winds, however westerly winds become more pronounced during the winter months (Callen 1981). Figure 2.6 illustrates the mean annual prevailing wind direction in the Lake Frome region.

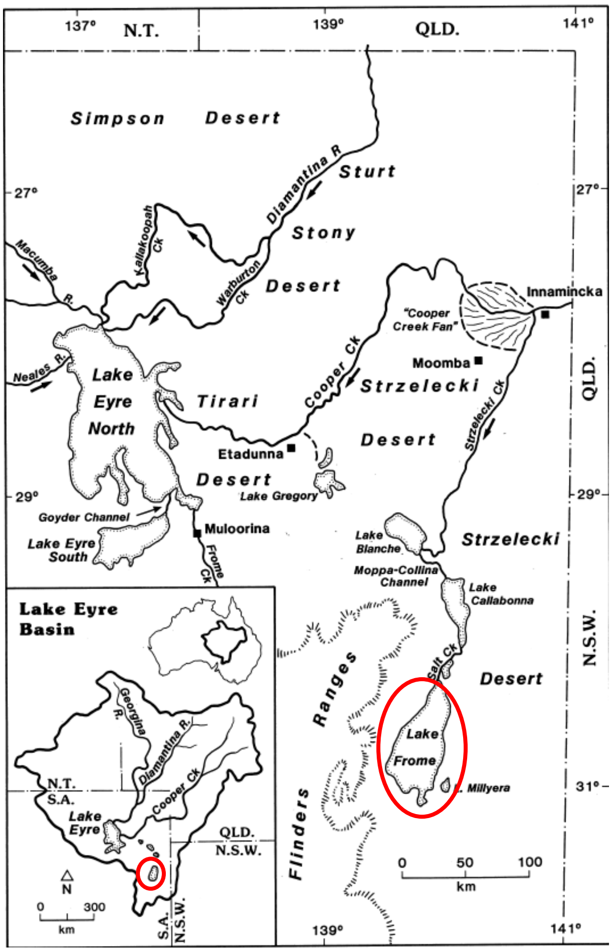

Figure 2.5: Map of the Lake Eyre Basin showing the palaeo-hydrological links between playa lakes, those of which that connect to the southern lakes; Lake Gregory, lake Blanche, Lake Callabonna and Lake Frome are dry or ephemeral today.
(Modified after Nanson *et al.* 1998).

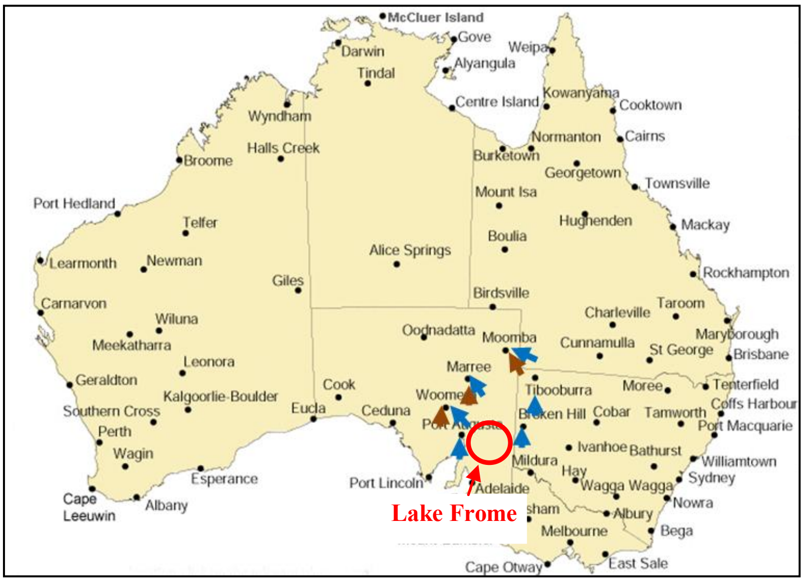

Figure 2.6: Prevailing direction of strongest winds around Lake Frome. Blue arrows = am; Brown arrows = pm (if different to am). (Modified after Bureau of Meteorology 2004).

The Lake Frome catchment encompasses an area of around 40,000 square kilometres with numerous ephemeral creeks rising in the Flinders Rangers to the west. (De Deckker *et al.* 2011). Creeks such as the Munyallina, Balcanoona and Big John Creek whose headwaters rise in the Flinders Ranges have an average rainfall higher than the surrounding plains at around 300 millimetres per annum, so it is these ephemeral creeks that currently form the main source of intermittent runoff to the lake (Draper & Jensen 1976; Nanson *et al*. 1998). Creek channels running from the Olary ranges in the south also drain towards Lake Frome but under the present climatic conditions these channels seldom carry water to the lake (Draper & Jensen 1976; Singh 1981).

Reports of significant runoff reaching Lake Frome are rare. Draper & Jensen (1976) report that Lake Frome had held some water in 1970 and that water covered 75% of the lake surface area during the 1974 floods and satellite photos show water in Lake Frome during the floods of 2011. Nanson *et al*. (1998) report that the water held in Lake Frome in 1974 was not received via Salt Creek and Lake Callabonna in the north despite reports of Lakes Gregory, Blanche and Callabonna receiving water from the Strzelecki Creek at that time (De Deckker *et al*. 2011). Instead the water received into Lake Frome during the floods of 1974 has been attributed to a combination of runoff from the Flinders Ranges and groundwater discharge (Cohen *et al.* 2011) and it is possible that the same occurred during 2011.

2.5 Lake Frome geomorphological setting

The current location and morphology of the major playa lakes including Lake Frome in the Lake Eyre basin are related to the existence of lineaments in the units of underlying aquifer sandstones which are marked by mound spring formations on the lake surface (Callen 1981; Wopfner & Twidale 1967). Structural control of the playa lakes by lineaments in the underlying sandstone units has resulted in lakes that are shaped as rectangular to elongate basins (Timms 1992, Figure 2.7). Waters from Great Artesian Basin aquifers are known to rise to the surface in the form of mound springs on the lake floor of Lake Frome and this has meant that the chemistry of the lake has been influenced as much by groundwater as it has by runoff (Draper & Jensen 1976; De Deckker *et al*. 2011).

In addition to structural controls other factors such as local topography and extreme climatic variations have been important in shaping playa lake geomorphology in the Lake Eyre basin. As discussed previously, high water lacustrine periods have created many relic shoreline features around the lakes forging the palaeochannels between lakes within the Lake Eyre Basin (Nanson *et al*. 1998). Low gradients within the basin and connecting channels between the lakes and the Cooper Creek drainage system, along with beach ridge deposits that stand metres above lake floor sediments, infer that certain hydrological tipping points in the basin have in the past led to basin wide fillings.

Periods of extended aridity in which the water tables beneath lake basins have dried resulting in lake floor deflation have been documented from aeolian deposits at Lake Eyre and Lake Frome (Magee et al. 1995; Magee & Miller 1995). Several large islands have been formed as a result in the southeast of the Lake Frome depression (Figure 2.6, Figure 2.7). Bowler (1976) and Callen (1983) report that the islands of Lake Frome were formed during the desiccation of the lake floor in a process where salts and clays of the lake floor dry with the retreat of the water table and are subsequently blown by strong winds to form islands composed of sand, clay and gypsum. The same islands have also been modified by periods of reactivated lacustrine conditions or ephemeral surface water flows forming cliffs and beach ridges around the islands.

Erosional mechanisms rather than those of deposition prevail across the basin today as dunes are built along lake shorelines from reworked deltaic sediment. The proximity of the Flinders Rangers to Lake Frome has meant that the streams rising in ranges supply the majority of sediment to the lake through deltas that intersect the western shoreline (Figure 2.8). As a result and as illustrated in Figure 2.8, the western shoreline from displays a large number of delta splay deposits and bars and/or spit like features whilst the eastern shoreline by contrast is relatively smooth and un-interrupted consisting of low beaches and low-rise lunettes (Callen 1976; Callen 1981).

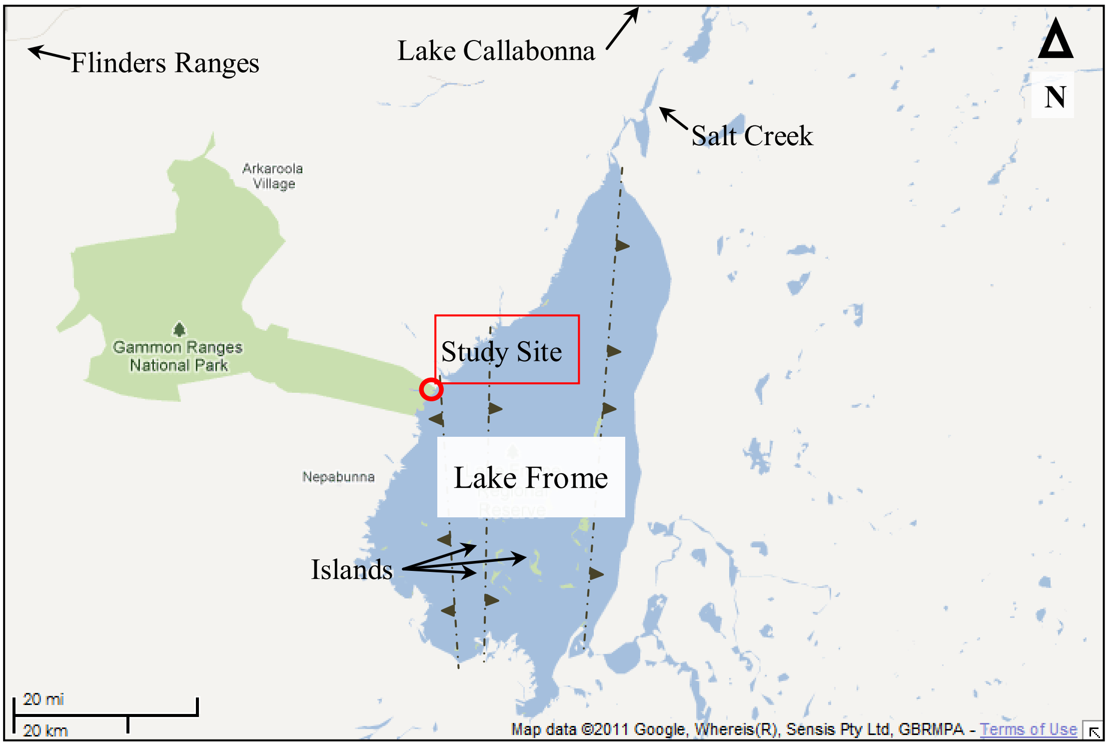

Figure 2.7: The elongate shape of Lake Frome as a result of the lineaments in the underlying sandstone units, fault lines shown by dashed lines.
(Fault lines from Draper & Jensen 1976; map modified from Mapland S.A. 2011)

2.6 Chapter summary

Lake Frome is a structural playa lake located within the Lake Eyre Basin between the Flinders Ranges and the Strzelecki desert in the arid centre of South Australia. The underlying geology of Lake Frome includes the southerly extension of Great Artesian Basin aquifers which at various times influence the chemistry of the groundwater at Lake Frome. Although dry to ephemeral today the Lake Eyre Basin is characterised by a series of channels which connect the five major playas in the basin and by shorelines forged by past mega-lake phases. Past lacustrine and fluvial phases have also left their signature on Lake Frome in the form of numerous bars, beach ridges and what appear to be spits in addition to palaeochannels that line the western shoreline. Whilst this is the case the majority of palaeoenvironmental studies have been focussed on lake floor sediments rather than shoreline features and it is these past investigations that are reviewed in the next chapter as part of the literature review.

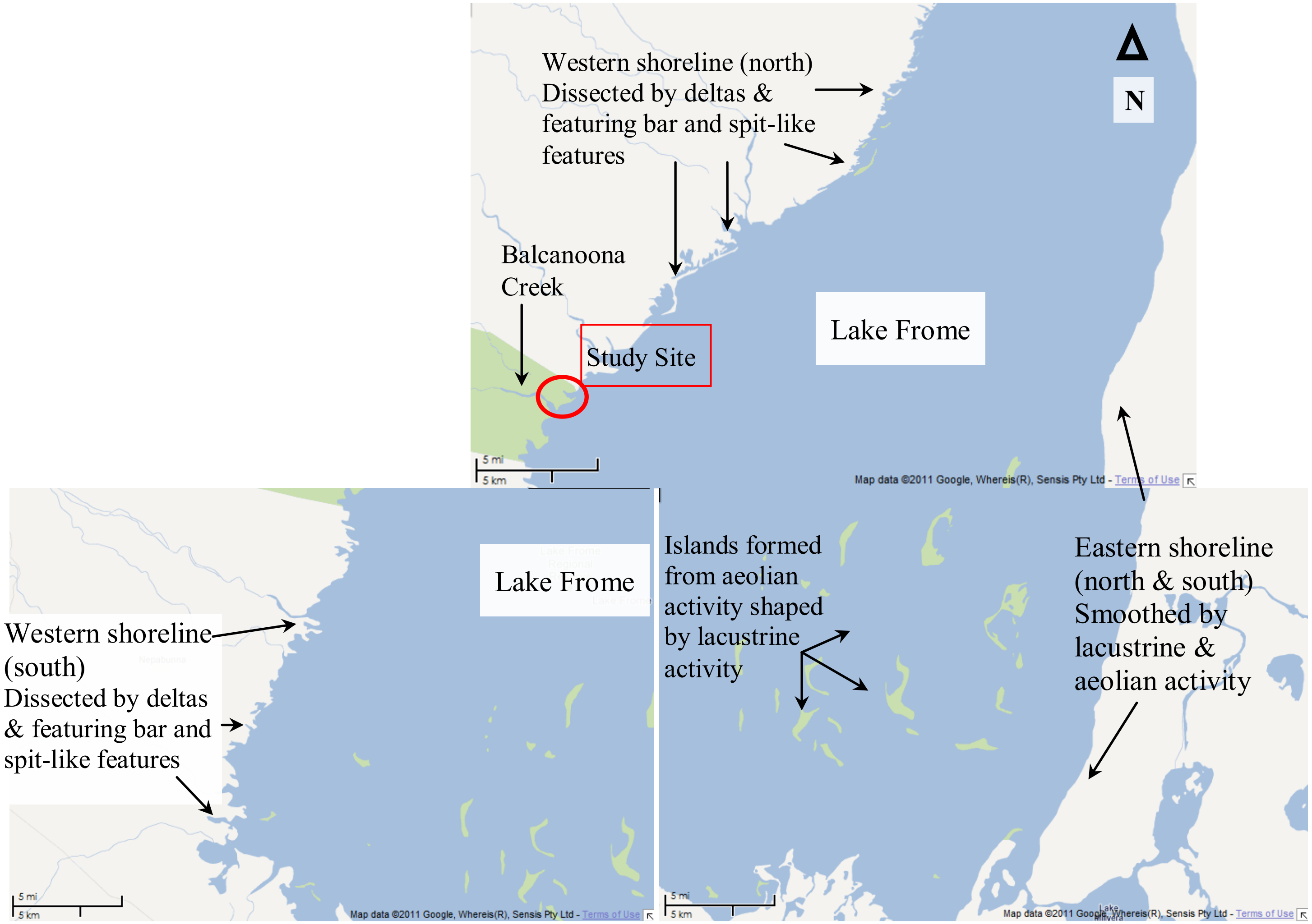

Figure 2.8: The shoreline morphology of Lake Frome a) North; including study site b) South-west c) South-east. (Modified from Mapland S.A. 2011)

Chapter 3: A review of the literature

3.1 Introduction

Lake Frome lies at the southernmost extent of the Lake Eyre Basin very near to the boundary of where both the winter rainfall from the south and the summer monsoon from the north penetrate into the continent. Lake Frome has been the topic of a variety of academic studies because of its unique location and because of its potential as a dry salt lake in an internal drainage basin, for holding information on the climate in the southern hemisphere during the Quaternary. Several palaeoenvironmental reconstructions of Lake Frome in the Quaternary have been carried out through stratigraphical and geochemical analysis of sediments. But because of its remote location and the difficulties associated with recovering samples from the playa lake it has meant that few palaeoshorelines have been investigated and only two different sets of cores from the lake floor have ever been analysed. Proxies that have been used to build palaeoenvironmental reconstructions include isotopic and pollen records, clay mineralogy and microfossil ecology and chemistry. Lake sediment deposits of organic carbon and carbonates have often been difficult to find in sufficient quantity at Lake Frome, but a small group of ages were produced by the radiocarbon dating method. More recently beach ridges and shorelines have been dated with the use of thermoluminescence (TL) and optically stimulated luminescence (OSL) dating methods which provide details of lake level heights and the timing of such occurrences.

3.2 Quaternary research at Lake Frome

3.2.1 Stratigraphy and geochronology

In an early study Draper and Jensen (1976) took a series of lake sediment cores and augured to 4 metres, from various locations including some to the south of the embayment study site (Figure 3.1). Radiocarbon ages were obtained from carbonaceous material found in fine sediment horizons of deltaic and lacustrine deposits and a cross section was constructed from the eastern shoreline at augur hole 63 to the centre of the lake at augur hole 49 as circled in Figure 3.1. Bowler *et al.* (1986) sampled cores to depths of 6 metres, taken 8km in from the western shoreline and about 17km in from the eastern shoreline as a part of the SLEADS project

(Figure 3.2). Dating the cores presented some difficulty as carbonate samples yielded radiocarbon ages that were one-half life older than organic carbon in stratigraphic succession, due to contamination by older carbonate. However radiocarbon ages from both carbonate and organic carbons produced chronologies, apart from a few reversals, thought to be consistent with sediment depths, enabling major lake phases to be constructed as a result.

The earliest works provide un-calibrated radiocarbon ages, for comparison purposes those ages have been calibrated using the Online CalPal system (2007) and will be ages denoted as cal. yBP from this point forward. It is unclear if papers discussed below and notably by Zheng and Bowler (1986) and Bowler and Magee (1988) present estimated ages in radiocarbon years BP or calibrated years BP where estimated ages have been us. Estimated years BP have been calibrated by use of the IntCal04 curve (2007) because error margins haven't been provided which prevents use of the Online CalPal system. Where ages have been calibrated estimated years BP they are denoted as cal. yBP.

3.2.2 Palynology

Singh (1981) conducted a study into the Holocene environment around Lake Frome by analysing the modern and fossil pollen and charcoal content of the lake floor sediments. This study on fossil pollens was carried by analysing fossil pollens from one centimetre segments on the one metre core (49 on Figure 3.1) taken in the Draper and Jensen (1976) study. Singh (1981) found that the vegetation record described significant changes with respect to the general climate and levels of moisture available to vegetation, and with regard to variations in the seasonal patterns of rainfall that fell around Lake Frome during the Holocene. Similarly Singh and Luly (1991) carried out a stratigraphical pollen analysis on core LF82/2 (LF 82/1-3 on Figure 3.2) extending the pollen record of the Frome area back to around 21,400 cal. yBP and finding similar Holocene climatic and ecological phases to those found by Singh (1981).

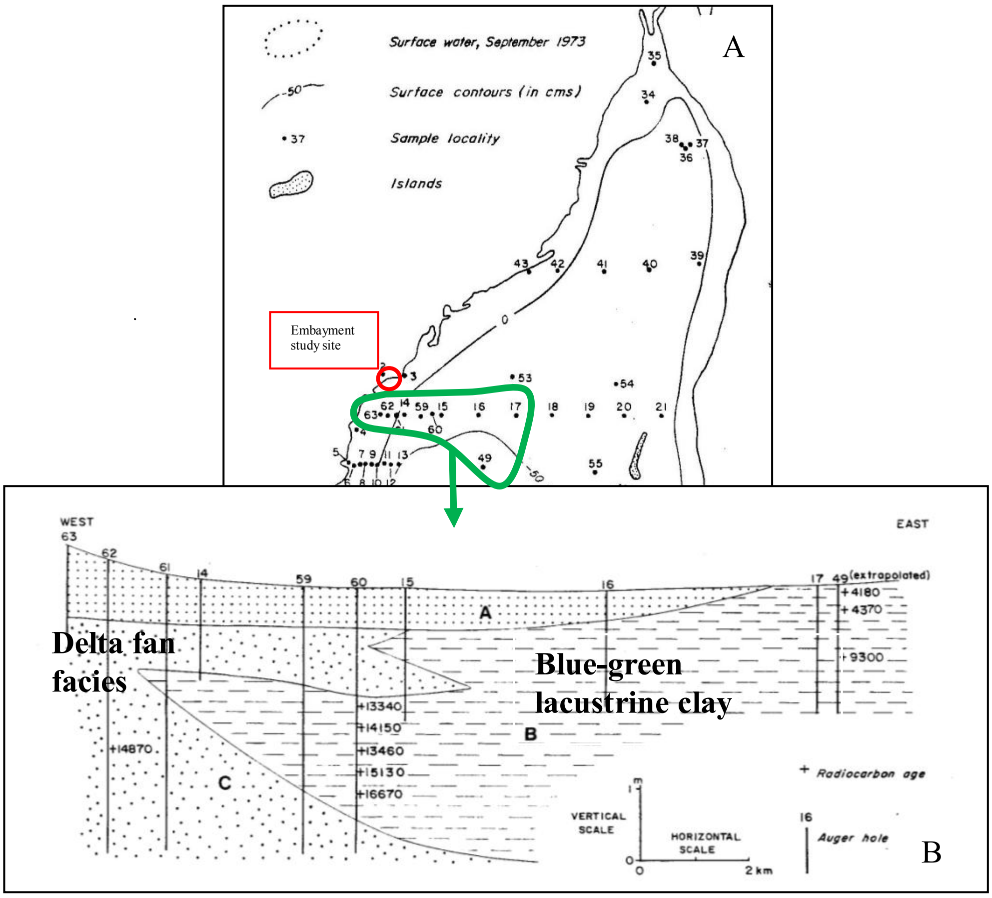

Figure 3.1:A) Map of augur and core holes by Draper & Jensen (1976). B) Transect from the western shoreline into the centre of the lake was constructed from the holes circled in green.

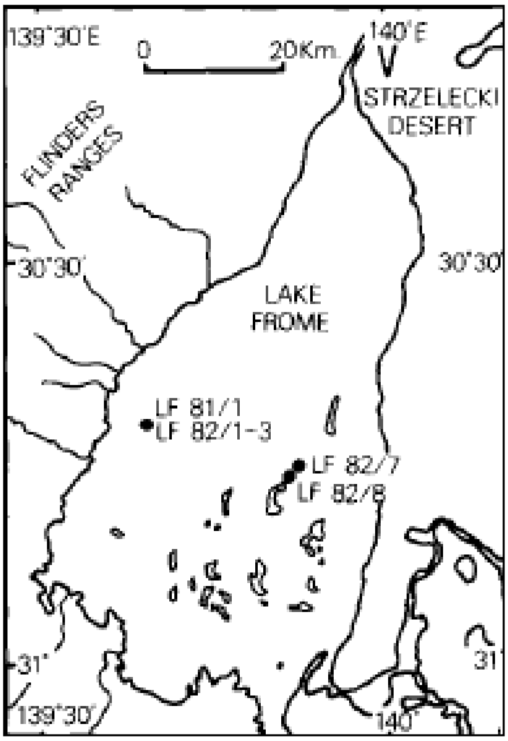

Figure 3.2: Map of cores taken by Bowler *et al.* (1986).

3.2.3 Geochemical analysis

Several geochemical analyses have been carried out on sediments, groundwater and microfossils from Lake Frome sediments. Draper and Jensen's (1976) chemical analysis of water and sediments found a high sodium chloride content of groundwater with incursions from aquifer waters high in bicarbonate and a minor elemental dispersion governed by distribution and variations in parent material.
Zheng and Bowler (1986) conducted a clay mineral X-ray diffraction (XRD) analysis of cores LF82/1-3 resulting in the identification of three broad phases in the depositional environment. Ullman and Collerson (1994) analysed the strontium isotope levels of sedimentary gypsum over a range of different depths and provided estimates of five wet and dry periods at the lake. Most recently De Deckker *et al.* (2011) presented a reconstruction of Lake Frome palaeohydrology from fossil ostracod Strontium/Calcium and Magnesium/Calcium ratios and ecologies from cores LF82/1-3 and LF82/7. De Deckker (2011) and also presented two new AMS radiocarbon ages extending the chronology of LF82/1-3 back to around 42 $\pm$ 417 cal. yBP and a lower disconformity.

3.2.4 Geomorphology and chronology of palaeoshorelines

Raised beach ridges around arid salt lakes representing palaeoshorelines from past climatic regimes have frequently been used for palaeoclimatic and chronological reconstruction of past environments (Torgersen *et al*. 1986). However the limits placed upon dating such sediment by radiocarbon have in the past meant that palaeoshorelines could be accurately dated to seventy five thousand years at the very most (Walker 2005). TL, OSL and Uranium-Thorium methods have been used more recently to overcome the age limit that radiocarbon dating presents. TL, OSL and TIMS U-Th ages obtained from palaeoshoreline deposits around Lake Frome and the other lakes and tributaries in the Lake Eyre Basin obtained by Croke et al. (1992), Nanson *et al*. (1998), Cohen *et al*. (2011) and Cohen et al. (In press) and currently provide the upper age limits for lacustrine or lake-filling chronologies for the Lake Eyre Basin deposition during the Quaternary. Geomorphological analysis and luminescence dating palaeoshorelines within the Lake Eyre Basin have given rise to our understanding of how at certain points the hydrology the Lake Eyre Basin becomes interconnected and how the lakes in the basin have been joined in the past to varying extents to from mega lakes. Due to the interconnectedness within the Lake Eyre Basin major studies in the basin such as those by Magee *et al.* (1995) on the Madigan Gulf in Lake Eyre and studies carried out to investigate regional climate and hydrology such as those by Williams *et al*. 2001 and Haberlah *et al*. 2010 on the Flinders Ranges silts are also reviewed below.

3.3 A synthesis of the literature on Lake Frome

3.3.1 Pleistocene Lake Frome

MIS 5 to MIS 3: (c. 110 ka to c. 25 ka)

Most authors agree that conditions were more humid or moist than present during the last interglacial and as a consequence a substantial and standing body of water filled the lake Eyre Basin during mid to late MIS 5. OSL and TL ages obtained from palaeoshorelines up to +15m (AHD) in the south of the basin suggest that basin-wide high water events occurred during MIS 5 with overflow between lakes in the southeast and to the north resulting in a water body that stretched from Lake Eyre to the southern lakes including Lake Frome via the Warrawoocarra channel (Nanson *et al*. 1998; Cohen *et al*. 2011).

Nanson *et al*. (1992) report a TL date of 111 ± 18 ka BP from a +13 metre (AHD) palaeoshoreline at Lake Eyre South which is correlated by evidence of a pluvial period by TL and U/Th ages of 109 ± 4 ka and 103 ± 4 ka from the fluvial sands of the Katipiri Formation. The Katipiri Formation consists of bedload sediments deposited by the large meandering ancestors of the Diamantina and Cooper Creek systems (Nanson *et al*. 1992). Magee *et al*. (1995) report a thick lacustrine clay sequence from Williams Point, and associated +10m (AHD) beach ridges located to the south of the Madigan Gulf which are thought to be equivalent to the fluvial sediments deposited in the Katipiri Formation. Fluvial channel sands dated by TL to 107 ± 15 ka and 106 ± 22 ka, that grade into deltaic and lacustrine deposits to the west of the Lake Eyre basin suggest that the Lake Eyre water body extended up to 35km west of the current playa lake limits and that high volumes of runoff were also flowing into the basin from Neales River in the northwest in addition to that from the north and northeast (Croke *et al*. 1996). In the southeast of the basin Cohen *et al*. (2011) have obtained late MIS 5 ages ranging from 109.9 ± 7.5 ka to 87.3 ± 5.8 ka from +15m (AHD) palaeoshorelines around lakes Frome and Callabonna. This evidence verifies the basin-wide extent of the major lacustrine period in late MIS 5. The spread of ages obtained by Cohen *et al*. (2011) are also consistent with Magee *et al*. (1995) reporting a series of shorter deep-water lacustrine phases at Williams Point just after 90 ka during MIS 5b, subsequent to the major MIS 5c lacustrine period.

MIS 4 appears to be marked by fluctuations between lacustrine and arid periods within the basin and a dominance of runoff from the south. Nanson *et al.* (1998) obtained three TL ages between 70 and 62 ka from aeolian sand at Lake Frome and from Lake Eyre South. In the Madigan Gulf Magee *et al*. (1995) report beach sand and gastropod shell from a -3m (AHD) shoreline of a reduced water still-stand which is overlain by aeolian sands with Genyornis eggshell that date to within this period. From the southeast of the basin Cohen *et al.* (2011) describe a second Lake Mega-Frome stage during MIS 4 from the +15m (AHD) palaeoshoreline at Lake Frome which provides OSL ages from 68 $\pm$ 4 ka to 60 $\pm$ 8 ka.

In early MIS 3 Magee *et al*. (1995) report a period of aridity and deflation from 60-50 ka in the Madigan Gulf in contrast to Nanson *et al*. (1998) who provide two ages of 55 $\pm$ 5 & 10 ka from palaeoshorelines to the northwest of Lake Frome and around the southern margin of Lake Eyre. Both Nanson *et al*. (1998) and Magee and Miller (1998) cite evidence of enhanced runoff in the south of the continent at this time which could explain the disparity between reports of aridity in the Madigan Gulf and lacustrine conditions in the southeast of the basin. Cohen *et al*. (2011) report similar southern basin-wide lacustrine conditions at this time from evidence of a +15m (AHD) palaeoshoreline around lakes Frome and Callabonna which yield TL and OSL ages between 48 $\pm$ 4 and 45 $\pm$ 4 ka. Nanson *et al*. (1998) also describes TL ages from beach ridge/palaeoshoreline deposits identified around Lake Eyre South from early MIS 3 at 47 $\pm$ 7 & 5 ka. Two TL ages of 51 $\pm$ 5 ka and 51 $\pm$ 4 ka from the shorelines of the Warrawoocara channel between Lake Gregory and Lake Eyre tend to back up this information and suggest that a high-stage southern basin at this time was flowing north into Lake Eyre (Cohen *et al.* In press, Cohen 2011 unpublished data UOW).

Cohen *et al*. (2011) describe palaeoshorelines at Salt Creek and Lake Callabonna at heights of +10m and +12m (AHD) that yield TL and OSL ages from late MIS 3. The ages given by Cohen *et al*. (2011) are 29 ± 2 ka and 33 ± 3 ka and 31 ± 3 ka and the authors argue that this lacustrine period probably occurred only in the south as similar ages have not been returned from shorelines further north in the basin. Beach ridges heights are also about 5m lower than those previously discussed so it is possible that volumes reduced by 5 metres may not lead to spillover to the north. Hence the lacustrine period reported by Cohen *et al*. (2011) in Late MIS 3 represents both a transition in climatic conditions in the basin and a changing hydrological regime where an abundantly moist climate and basin-wide high-water filling events appear to give way to that of reduced moisture and the dominance of a more local hydrological regime. Lake Frome core analyses by De Deckker *et al.* (2011) from within the Lake Frome core horizon support a late MIS 3 high water episode. Ostracod fossils of freshwater affinities, interpreted as evidence of deep water events in Lake Frome were found by De Deckker *et al*. (2011) within horizons dating from around 40,300 to 29,600 cal. yBP along with low fossil Sr/Ca values which indicate that moisture supply and runoff were sufficient to maintain a permanent water body over the period. Fossil species dated from around 29,600 to 25,000 cal. yBP indicate a permanent water body in Lake Frome, but increasing water salinity suggestive of falling water levels and a progression towards ephemeral conditions in the lake.

MIS 2 (c. 25 ka to c. 15 ka)

The LGM is thought to have occurred from around 23,000 to 19,000 cal. yBP (De Deckker 2011). It is generally accepted that the onset of the LGM brought reduced temperatures; reduced precipitation and heightened wind activity to central Australia (Bowler 1976; Fitzsimmons *et al.* 2007). However evidence of LGM aridity and high precipitation deposition appear to occur simultaneously in the Lake Eyre basin and in the Flinders Ranges adjacent to Lake Frome. Whilst many authors report widespread aridity, playa deflation and aeolian deposition during MIS 2, Nanson *et al.* (1998) recovered two early MIS 2 TL ages of 26.2 ± 3.7 ka and 22.8 ± 2.3 ka BP from adjacent + 0.8 metre and + 1.0 metre AHD units of sand and shell beach ridge deposits at Lake Eyre South. Both Magee *et al*. (1995) and Magee and Miller (1998) report deflationary events in the Madigan Gulf during this time; a lowering of lake floor sediments to the present -17 metre AHD level between 25 and 10 ka and the aeolian deposition of the Shelly Island unit from 34,000 to 15,000 cal. yBP (calibrated from CalPal) with concentrated activity between 24,000 to 20,500 cal. yBP (calibrated from CalPal).

Radiocarbon analysis of the carbonate within the aeolian sediments that form the islands of Lake Frome in the south east of the lake, have provided four ages in ascending order from 23,450 ± 500, 22,025 ± 380, 19,875 ± 380 to 24,230 ± 420 cal. yBP (calibrated from CalPal) and represent lake floor erosion and deposition by persistent winds under an extended period of aridity (Bowler 1976; Callen 1983b). Zheng and Bowler's (1986) study of clay mineralogy by X-ray diffraction (XRD) on the cores LF82/1-3 (Figure 3.2) show a likelihood that sediment was derived from multiple and distal sources and deposited in a dry climate between 23 and 19 ka BP. A low pollen count indicates scarcity of vegetation at around the time of the proposed LGM disconformity was also found by analysis of pollen content in the core LF82/2 by Singh and Luly (1991).

Other evidence suggests that aridity did not extend over the entirety of the region. Thick segments of LGM deposited fine grained laminated sediments up to 7 metres deep are found within Brachina Gorge in the Flinders Rangers. The fine grained Brachina Silts have been identified as loess blown from the west and deposited in the Flinders Rangers under fluvatile, lacustrine or wetland environments (Cock *et al*. 1999; Williams *et al*. 2001; Haberlah *et al*. 2010). Plant and gastropod remains from the silt laminations have been dated by AMS to provide an age range from 29,000 radiocarbon years (beyond the range of calibration) to around 17,000 cal. yBP, ages which reveal that deposition took place prior to, during and after the LGM in an environment of plentiful moisture (Williams *et al*. 2001). The presence of the fluvial, lacustrine or wetland deposited silts in the Lake Frome catchment of the Flinders Rangers during this time must certainly mean that we cannot rule out episodes of runoff and reactivation of lacustrine conditions within Lake Frome during the LGM.

Fossil species analysed by De Deckker *et al.* (2011) from within the Lake Frome core horizon also indicate high salinity indicators present within the 25,000 to 20,200 cal. yBP, suggestive of low to ephemeral water in the lake, however two horizons are also reported with freshwater indicators. Bowler *et al.* (1986) also reported fine blue-grey clay sediments of a high water lacustrine phase below a disconformity (at 3.5 metres) which they interpreted as LGM deflation. Denoting an age just prior to that recognised as the height of the LGM, in which Lake Frome contained a standing water body.

Following the LGM several analyses of the lake floor sediments from Lake Frome provide detailed and for the most part analogous descriptions of the hydrological, environmental and climatic conditions within the Lake Frome catchment. Although the reported ages often vary by a few thousand years, most studies on lake floor sediments of Lake Frome agree that lacustrine conditions recovered in Lake Frome after the LGM. Although De Deckker (2011) reports the presence of low salinity ostracod species and the absence of gypsum from only a thin section in the cores around the inferred ages of 21,300 to 20,200 cal. yBP, they do indicate that a standing waterbody would have existed in the lake. Draper and Jensen (1976) identified a westerly transgression of lacustrine blue-green clay and mud from their transect of cores 62 to 60 (Figure 3.1). This sequence was interpreted as lake expansion and stabilisation of lake water levels and was dated from organic carbon to between 20, 045 $\pm$ 830 and 16,175 $\pm$ 620 cal. yBP (calibrated from CalPal).

Bowler *et al.* (1986) also identified a high water lacustrine phase from the dark grey clay content of core LF82/1-3 lying above the LGM disconformity. Organic carbon from the clay and silt sediments yielded ages ascending from 20,405 $\pm$ 400 to 16,490 $\pm$ 490 cal. yBP. This phase was thought to be representative of rapid deposition of sediment in a lacustrine environment with high silt content from concurrent or reworked wind-blown dust from LGM sediments. Wet conditions at deposition were also favoured by the clay mineralogy of sediment dated from around 19 to 14 ka BP by Zheng and Bowler's (1986) XRD study of clay mineralogy. It appears that lake levels during this time were high enough for spillage between lakes Frome and Callabonna but not for overflow to Lake Eyre. Cohen *et al.* (2011) also reports OSL ages of 17 and 15 ka from a +7m (AHD) palaeoshoreline around Lake Callabonna and at Salt Creek and another 13 ka date from raised beach deposits at Salt Creek.

An increase in pollens also demonstrate recovery of moisture in the environmental following the LGM disconformity described by Bowler *et al.* (1986). In core LF82/2 a gradual increase in the number of fossil pollen grains were found by Singh and Luly (1991), the fossil pollens indicate a recovery of vegetation to the extent that it appears that open woodlands surrounded the lake between 21,000 and 17,400 cal. yBP. Relatively higher numbers of winter rainfall dependant herb pollens and low fern spores also appear to indicate that low temperatures, dry summers and wet winters dominated the climate at this stage.

Following this recovery both Draper and Jensen (1976) and Singh and Luly (1991) describe a reduction in moisture availability at Lake Frome. Decreases in all pollen numbers are reported except for those of ephemeral taxa between 17,000 and 15,000 cal. yBP and as illustrated in Figure 3.1, Draper and Jensen (1976) report progradation of delta fan facies along the western shoreline from around 16,000 cal yBP indicating the onset of a dryer climate with a reduction of available moisture in the lake environment and a fall in lake levels . Moisture availability appears to increase again from analysis of core LF82/2 though after around 15,000 cal. yBP when pollen numbers representing ferns and subtropical species increase indicative of higher temperatures and likely higher incidence of summer monsoonal rains (Singh & Luly 1991). However the transect by Draper and Jensen (1976) appears not to record a change from delta fan progradation or reduced lacustrine conditions in the west.

3.3.2 Holocene Lake Frome

MIS 1 (c. 15 ka to c. 5 ka)

At a depth of around 1.0 metre Bowler *et al.* (1986) described oxidised clays and the onset of reduced water levels dated at around 12,670 ± 405 cal. yBP. A reduction of moisture availability is correlated by the clay mineralogy study as Zheng and Bowler (1986) found a greater variety of minerals which indicates multiple distal sources and high illite crystallinity between the ages of around 14 ka to 10 ka BP indicating deposition under dry lake conditions.

Draper and Jensen (1976) described delta fan progradation with an overall fall in lake levels commensurate with increasing aridity from around 16 cal. yBP. They also returned a series of younger radiocarbon ages 10,660 ± 855, 6,335 ± 285, 4,970 ± 315 and 4,680 ± 745 cal. yBP from further towards the centre of the lake indicating that the lake was shrinking but not entirely dry across that period. De Deckker (2011) reported a wet, lacustrine period between around 12,000 to 11,600 cal. yBP from the abundance of fresh water taxa in core segments. Singh (1981) identified a pollen zone depicting a wet period estimated from the radiocarbon ages obtained by Draper and Jensen (1976) to be at around 10,750 cal. yBP (calibrated from Intcal04). A wet period was identified from the high percentages of all pollens found in the core sections, including trees, tall shrubs, low shrubs and grasses including water-course dwelling vegetation unlikely to be found around the lake today. Due to the high incidence of summer rain dependant grasses, Singh (1981) determined that the northerly derived summer monsoons occurred more regularly and possibly with greater intensity in this period than compared with today's climate. The increased summer rainfall trend is confirmed in the Singh and Luly (1991) study of core LF82/2.

Following this Singh (1981) described the core section with inferred date of around 9,000 cal. yBP as a period of extreme climatic instability. Bowler *et al.* (1986) interpret oxidised clays through1.0 metre to a sand layer at 0.5 metres in cores LF82/1-3 as a dry lake phase between the inferred ages of 9,000 and 8,500 cal. yBP. During this time the charcoal content within the core appears to increase and the pollen of vegetation ecologically suited to ephemeral conditions also increases whilst all others decline suggesting a reduction in both summer and winter rainfall (Singh 1981).

A final lacustrine period of some permanence appears to have occurred at Lake Frome just prior to five thousand years ago. Singh (1981) reports an increase in pollens from tree and grass species in the core section at around 7,800 to 5,100 cal. yBP, which indicates a resurgence of regular monsoonal rainfalls as a moisture source to the Lake Frome area. Palaeoshorelines at heights of +4 metre AHD around

Lake Callabonna and Salt Creek were analysed by Cohen *et al.* (2011) and returned a series of OSL and AMS ages ranging from 4.5 to 5.58 ka.

A thin layer of non-oxidised clays at 0.4 metres are interpreted as a probable short term deeper water onset at around 6,500 cal. yBP by (Bowler *et al.* 1986). This phase is similar to one reported by Singh and Luly (1991) who describe the pollen content of LF82/2 at around the inferred date of 6,500 cal. yBP as high in grass and tree pollen numbers, indicating increased moisture availability in the environment for a short period.

MIS 1 (c. 5 ka to the present)

All analyses of Frome sediments appear to agree that the most recent half of the Holocene has been a relatively dry period. Bowler *et al.* (1986) describes the onset of modern dry to ephemeral conditions in Lake Frome from the presence of uninterrupted oxidised sandy clay to surface sediments occurring from around 5,700 cal. yBP. Whilst analyses from Singh (1981) and Singh and Luly (1991) report a reduction in tree and grass pollens from around 5,000 cal. yBP to the present, indicating a general reduction in available moisture especially with regard to the summer monsoonal rainfalls. However both Nanson *et al*. (1998) and Cohen *et al*. (2011) report a return to lacustrine conditions subsequent to 5 ka. Nanson *et al*. (1998) report TL ages ranging from 1.0 to 2.2 ka from a beach ridge and spit system around Lake Callabonna at heights of +6 and +4 metre AHD. Cohen *et al*. (2011) also report an OSL date of 0.96 $\pm$ 0.07 ka from a +4 metre AHD beach ridge at Salt Creek, all of which correspond to the medieval warm period which was experienced throughout the world at that time.

3.4 Chapter summary

The existing literature on Lake Frome and the Lake Eyre Basin describes several broad stages in the climate and hydrology of the basin in which a southern and/or northern source of runoff can be inferred. During the last interglacial late MIS 5 the Lake Eyre Basin formed a vast and interconnected mega lake 13m to 15m (AHD) deep in which runoff was high from tributaries in the north and in the south. MIS 4 marked possible fluctuations in lacustrine and arid conditions but also a change to the dominance of runoff from the south as the southern lakes filled to +15m (AHD) whilst Lake Eyre filled to -3m (AHD) in the Madigan Gulf. Lake levels in the southern basin also filled to +15m (AHD) again during MIS 3 with possible overflow from the south to the north of the basin. The southern lakes filled to +10m and +12m during late MIS 3 but this appears to have occurred only in the south of the basin and following MIS 3 a transition occurs as conditions become generally dryer and the lakes become dominated by local hydrological factors. Evidence of the conditions at Lake Frome during the LGM comes from islands in the lake which were built from the deflation of the lake surface and low pollen counts but reports of enhanced runoff in the nearby Flinders Ranges during this period add uncertainty to reports that this period was dominated by aridity and desiccation. Most accounts agree that runoff to Lake Frome increased again following the LGM from around 17 to 12 ka but fillings on a basin-wide scale were not experienced again. Fluctuations of shallow lacustrine and ephemeral conditions followed this with a return to local lacustrine conditions at around 5 ka in Lake Frome. Conditions during the last five thousand years throughout the Lake Eyre basin and at Lake Frome have been marked by widespread aridity as the lakes transitioned to stable playa environments, broken only by a reported lacustrine interlude during the medieval warm period

Chapter 4: The Stratigraphy and geomorphology of the study site

4.1 Introduction

This chapter provides a description of the stratigraphy and geomorphology of the study site at Lake Frome. Samples and spatial data were collected and numbered by hole at the site along three transect lines, each of which extended from the margins of the study site to the playa lake floor. Details of the sediment content and type were documented and grain size analysis was carried out by laser diffraction in the Malvern Mastersizer. The geochemistry of the sediment from two holes was measured by X-ray diffraction (XRD). Stratigraphic logs were constructed (Appendix 4.4, Appendix 4.5 and Appendix 4.6) from field notes and from the data obtained through sediment analysis. The stratigraphic logs were then used to identify the major depositional units at the site. Illustrations of the three transects were then created to demonstrate the associations and extent of each of the units throughout the embayment. Lastly the raised landforms to the north and south that define the embayment appear as a northern shoreline and a bank attached spit, however, further investigation revealed that neither contained the bedding nor materials that are characteristic of beach ridge formation. In order to determine their mode of deposition an analysis was carried out on the grain size associations of these sediments.

4.2 Methods

4.2.1 Site location, access and permissions

The study site is located along the western shoreline of Lake Frome just north of the Balcanoona Creek delta (Figure 4.1, Figure 4.2). The site encompasses the embayment lake floor, a raised and elongate shore-attached ridge feature and a bench that frames the embayment to the north. Permission was sought and granted by the Government of South Australia, Department of Environment and Natural Resources and Department of the Premier and Cabinet Aboriginal Affairs to undertake scientific research in the Vulkathunha Gammon Ranges National Park and in the adjacent Lake Frome Regional Reserve (Appendix 4.1, Appendix 4.2). Research and data gathering included collecting sediment cores, auguring, trenching and sediment sampling whilst spatial data was gathered using GPS and a laser theodolite. This research was carried out at the site from the 19th to the 23rd of May 2011.

Figure 4.1: Location of study site at Lake Frome.
(Geoscience Australia (2005) 1:500 000 topographic map)

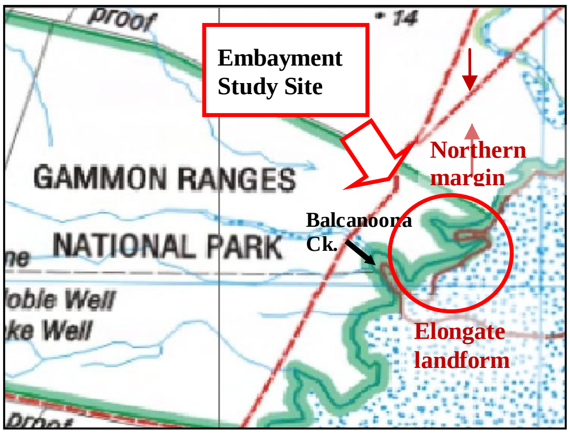

Figure 4.2: Detail of the study site along the western margin of Lake Frome
(Geoscience Australia (2005) 1:500 000 topographic map)

4.2.2 Trenching, coring, auguring and spatial data

Sediment samples were collected at 33 locations at the study site by coring, trenching and auguring (Figure 4.3). Five vibracores were collected in two or three sections each. These sediment cores were collected in aluminium pipe**s** of 75mm diameter through the operation of a quadrapod and vibracore drilling equipment. Trenches were dug by hand with shovel and spade at twenty eight sites and auguring was carried out with a hand auger with a 75mm head at twenty seven of the transect sites.

Coordinates for each sample location were collected with a hand held Trimble GeoXH geographical positioning system (GPS) fitted with TerraSync software and a map of sample sites was created (Figure 4.2). GPS coordinates were post-processed online through the CORSnet-NSW network (2010). Post-processing takes advantage of ionispheric and tropospheric modelling which fits corrections to the errors that occur between satellite transmission and reception of the positioning signals at the GPS unit (Janssen *et al.* 2011). Post-processing of the positioning data collected at Lake Frome was carried out through the nearest CORSnet-NSW station at Tibooburra, but because the station is more than 150km away from the study site, accuracy to within the sub-meter is not guaranteed and the error margin is unknown.

Because of the remoteness of the study site it was not possible to collect elevations corrected to Australian height datum (AHD), however values should be quite close to AHD. Heights and elevations given in this thesis were taken from the shoreline position on transect A using a laser theodolite. Elevations recorded on the theodolite were also grounded to a benchmark fence-post that was established for replication and verification at the north-western tip of the elongate landform near hole 16. Elevations taken on the theodolite are denoted hereafter as local height datum (LHD).

4.2.3 Grain size analysis

Sediment size, frequency and distribution data set provides insight into environmental and depositional parameters. An analysis of clay, silt and sand percentages by grain size was carried out on the sediment collected from the Lake Frome site using the Malvern Mastersizer 2000 Laser Diffraction Unit. Particle size is measured to international standard ISO13320-1 by the angle of reflected laser light passing through photosensitive detectors (Malvern Instruments 2000). The sediment from Lake Frome was analysed by employing the standard operating procedure with one minute of ultrasonic dispersion and using water as the dispersant. Laser intensity of the unit averaged 68.9%, the pump speed was 2850 revolutions per minute and the ultrasonic intensity was set to 13.5.

Information on sediment characteristics such as hue, gravel, gypsum and carbonate content was added to the data obtained from grain size analysis to form a record that describes a comprehensive set of characteristics for each of the sediment samples (Appendix 4.3). Grain size frequency data obtained from grain size analysis were graphed on logarithmic scale graphs in order to demonstrate single, bimodal or trimodal grain size groupings in the sediment**.** On the basis of grain size frequencies, sediment content and hue, stratigraphic logs and transects were constructed to demonstrate the history of deposition at the study site (Appendix 4.4, Appendix 4.5, Appendix 4.6).

4.2.4 Geochemistry

The sediment from holes 3 and 18 from sites on the lake floor were singled out for geochemical analysis. Sediment samples were ground to talc-like consistency with an agate mortar and pestle. For XRD analysis the sediment was then pressed into aluminium holders and analysed in a Phillips 1130/90 diffractometer with Spellman DF3 generator set to 1 kilowatt. This 1 kilowatt energy was achieved by setting the diffractometer to 35 Kv and 28.5 Ma. The samples were loaded into an automatic sample holder and analysed between 4°C and 70°C 2-theta at 2 degrees per minute with a step size of 0.02. Traces were produced through a GBC 122 control system and analysed using Traces, UPDSM and SIROQUANT.

For X-ray fractionation (XRF) trace mineral analysis the refined sediment powder was amalgamated with polyvinyl acetate, pressed into 5 to 5.5g discs and baked at a temperature of 70° Celsius for at least 2 hours. For XRF major element analysis 1g of powdered sediment was heated to 1050° Celsius for two hours to determine loss on ignition. Additional powder was combined with sodium metaborate, fused and pressed into glass discs to be inserted into the XRF machine. The samples were analysed using the Spectro Xepos energy dispersive XRF using propriety software and suitable standards.

4.3 Embayment stratigraphy and geomorphology

Three detailed stratigraphic transects were produced from the grain size data and the stratigraphic logs (Appendix 4.4, Appendix 4.5, Appendix 4.6). Transect A is a cross-section from the embayment margin in the north of the study site across the embayment and the elongate landform to the currently active delta. Transect B is a cross-section along the long axis of the elongate landform. Transect C is a cross-section that runs from the elongate landform to the centre of the inner-embayment (Figure 4.3).

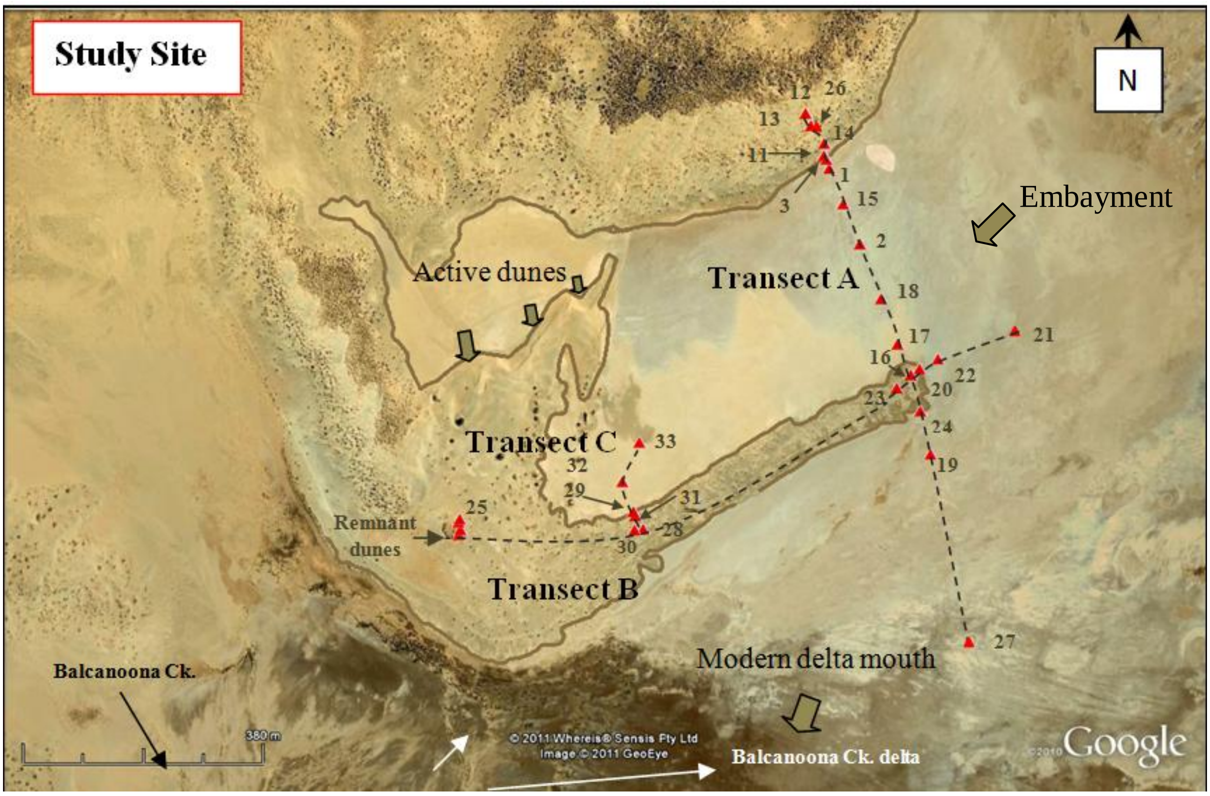

Figure 4.3: Map of study site marking the embayment and margins and trench and core holes and transect locations (Image from Google Earth 2011; holes and borders from CORSnet (2010) corrected data)

4.3.1 Transect A

Northern margin of embayment

Transect A spans the lake margin and adjacent playa floor and comprises holes 12 to 27 (Figure 4.4). Holes 12 and 13 are located along the top of the shoreline to the north of the embayment and were augured to depths of 6.3m and 6m respectively. At hole 12 on the dune crest the sediments consist of 4.5m of well sorted, fine to medium-grained dune sands (averaging 215µm - Appendix 4.3) which fine down slightly towards the base of the unit and continue in a thinner unit of 1.45m across the top of hole 13 (see stratigraphic log Appendix 4.4 for LHD heights). The composition of the sands changes at 4.5m (LHD) to a thin palaeosol with calcrete/gypcrete and a higher proportion of fines (~40% - Appendix 4.3).

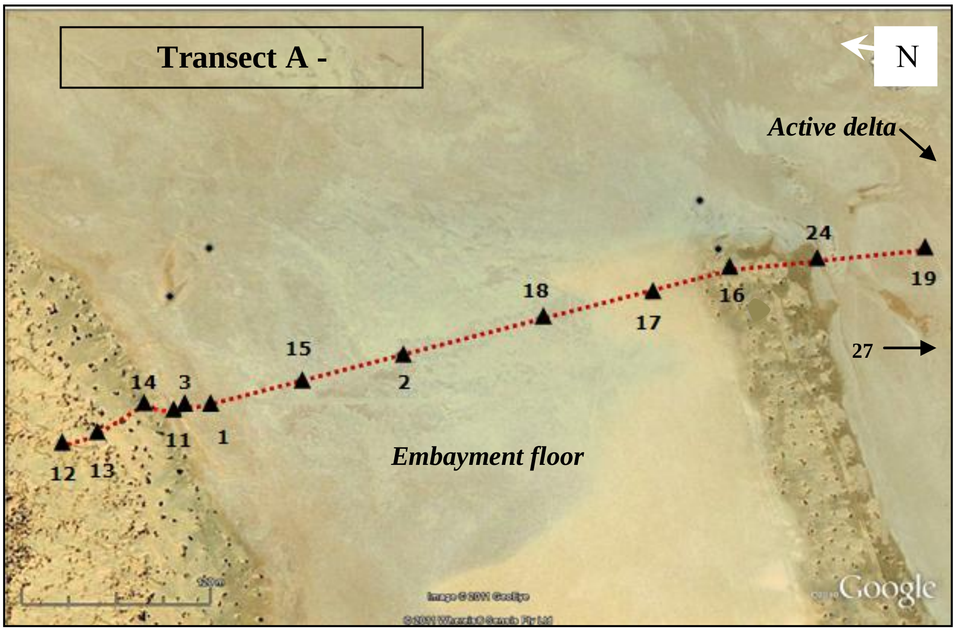

Figure 4.4: Locations of trench and core holes in Transect A
(Image from Google Earth 2011)

Below the palaeosol sands a massive, medium-grained sand unit extends across holes 12, 13 and 14 (Appendix 4.4). The massive unit has as much as 30% silt content, contains lenses of granules and well rounded pebbles (60mm b axis) and hence is very poorly sorted (sand, silt & clay averaging 2.2 θ - Appendix 4.3). At hole 14 this unit outcrops on the lake margin where it appears as a tabular bench armoured with pebbles and takes on the morphology of a shoreline above the playa lake floor (Figure 4.4, Figure 4.5). Although this unit appears as a shoreline above the playa lake floor, the sediments contain no beach debris such as mollusc, bivalve, charaphyte or fish remains which are described by Magee *et al*. (1995), Nanson *et al.* (1998) and Cohen *et al.* (2011) in their account of palaeoshorelines from around Lake Eyre and Lake Frome. Nor does it contain bedding that would indicate that it was built from lateral accretion. Prior to further analysis this unit is interpreted as fluvial sands that have been deposited in a fluvial delta. Evidence of aeolian modification of this unit is obvious from the dune systems that extend across holes 12 and 13 and as a result of the removal of the sand sized sediment the unit has a covering of pebbles. The pebble armoured shoreline therefore is the result of post-depositional deflation and dune building. Post depositional alteration of this unit and confirmation of the likeliness of this unit as the source of both the palaeosol and dune sands is evidenced in the comparison of grain size frequencies for each of these units (Figure 4.6).

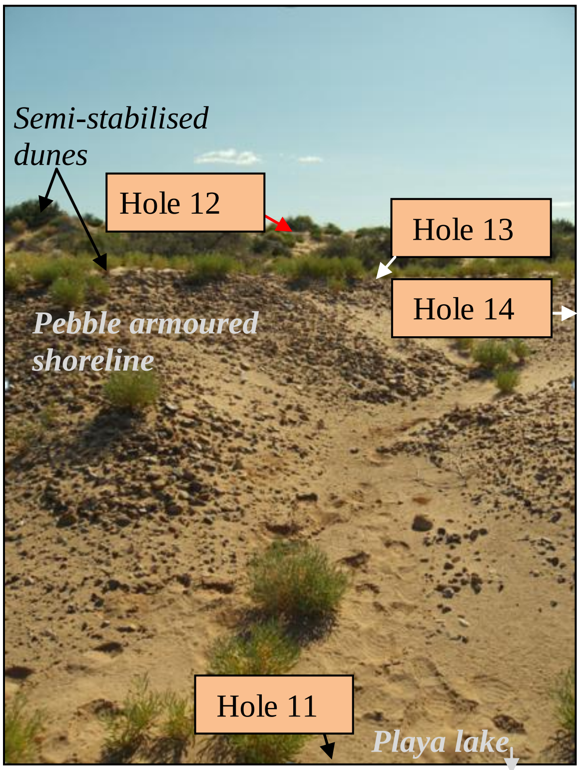

Figure 4.5: View from hole 11 on the playa lake floor of pebble armoured bench topped by dunes where holes 12, 13 and 14 are situated.

Underlying the fluvial sand unit at holes 13 and 14 are fine to very fine-grained sands silts and clays (~ 60% silt and clay - Appendix 4.3, see stratigraphic log Appendix 4.4 for details). The sand, silt and clay unit is a fining up sequence 1.35m thick of oxidised sediments that are yellowish red in colour with a small amount of selinite.

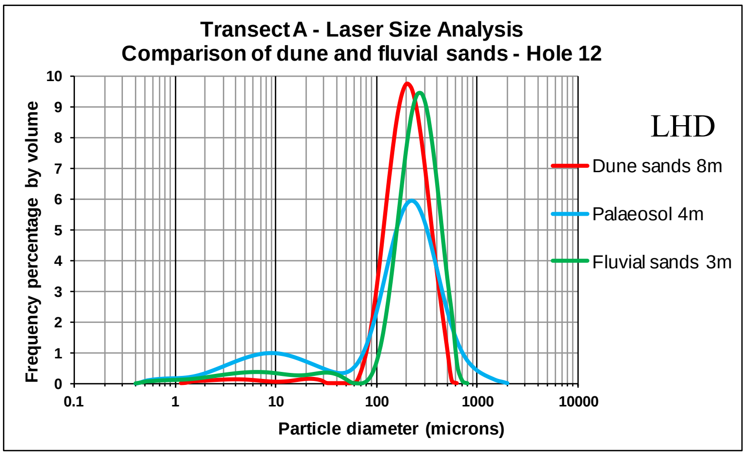

Figure 4.6: Grain size frequency comparison of dune and fluvial sands.

This unit proves a large reduction in grain size (from 385 to 70µm - Appendix 4.3) and hence depositional energy from the fluvial unit, it also overlies a thin layer of reducing (gray-green in colour) silt (75-80% silt & clay - Appendix 4.3) and is therefore interpreted as lacustrine or pro-deltaic in origin. Beneath the lacustrine sediments a thin unit of very fine-grained sand overlies a layer of well rounded pebbles (b-axis 25mm) at ~ 0.8m (AHD, see stratigraphic log Appendix 4.4 for details). The basal unit at the lake margin consists of compact lacustrine clays (80-95% silt and clay, Appendix 4.3) which are discussed in detail in the following section.

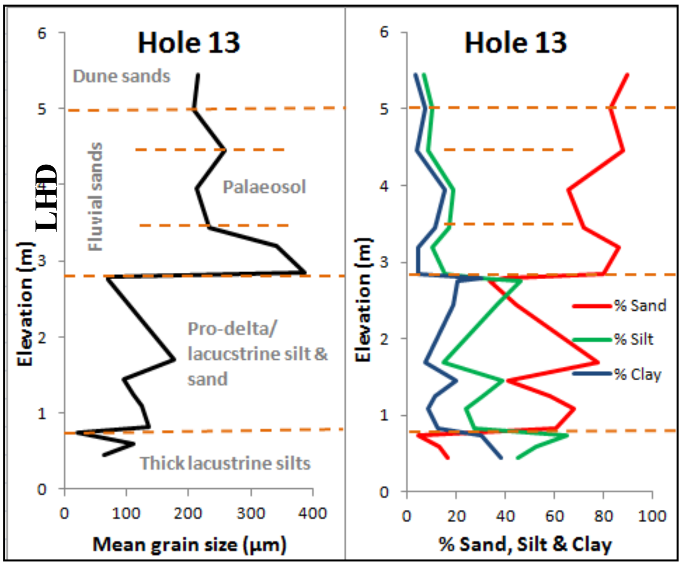

Figure 4.7: Hole 13 – mean grain size and percentages of sand, silt and clay.

Figure 4.7 demonstrates the transitions that occur between each of the units in hole 13 through changes to the mean grain size and the relative contents of sand, silt and clay. This diagram demonstrates the fluctuations in depositional energy and modes of deposition that have built the margins of the lake at this site. Moving up from the base this site has seen lacustrine, pro-deltaic and fluvio-deltaic deposition and finally aeolian redistribution of the sediment has resulted in the capping dunes and the pebble armoured bench.

Embayment Floor

Holes 11 to 17 are located along the lake floor section of the embayment (Figure 4.4). At an elevation of around 2-2.5m (AHD) the playa lake floor surface has a thin (2-3mm) and patchy cover of white precipitated salts. The uppermost sediments of the embayment lake floor consist of ~0.15-1m thick fine to very fine-grained, highly oxidised red-brown sands with a silt and clay matrix content of around 20% (-Appendix 4.3). Thin horizontal laminations are occasionally visible within the sands and two lenses of finer sediments (~30-90μm - Appendix 4.3) are found within the surface sands in holes 2 and 18 towards the centre of the embayment (see stratigraphic logs Appendix 4.4 for details). For the most part the lake surface sands are massive, due in part to the growth of displacive seed and discoidal gypsum between sediment grains close to the surface (Figure 4.8).

Holes 11 and 3 are located at the base of the northern bench on the lake floor (Figure 4.5) where trenches were opened to depths of 1.3m and 1m respectively. A gray-green lacustrine silt and clay (75-80% silt & clay - Appendix 4.3) similar to that which runs through holes 13 and 14 is found beneath the highly oxidised surface sands in holes 11 and 3. This reduced unit fines out to interfinger with a unit containing multiple horizontal laminae of fine to very fine-grained sands (Figure 4.8). The laminae of silt, clay and sand continues across the embayment to hole 17 in a unit around 1m thick that dips slightly to the south. Gypsum in the form of small (~10-250mm) prismatic crystals of selinite and rosettes are found throughout this sequence and selinite that forms sub-aqueously was found in holes 2 and 3. The sequences of sand and silt plus clay laminae are interpreted as flucutatings of fluvio-deltaic discharge at close proximity to the source and nearshore lacustrine deposition.

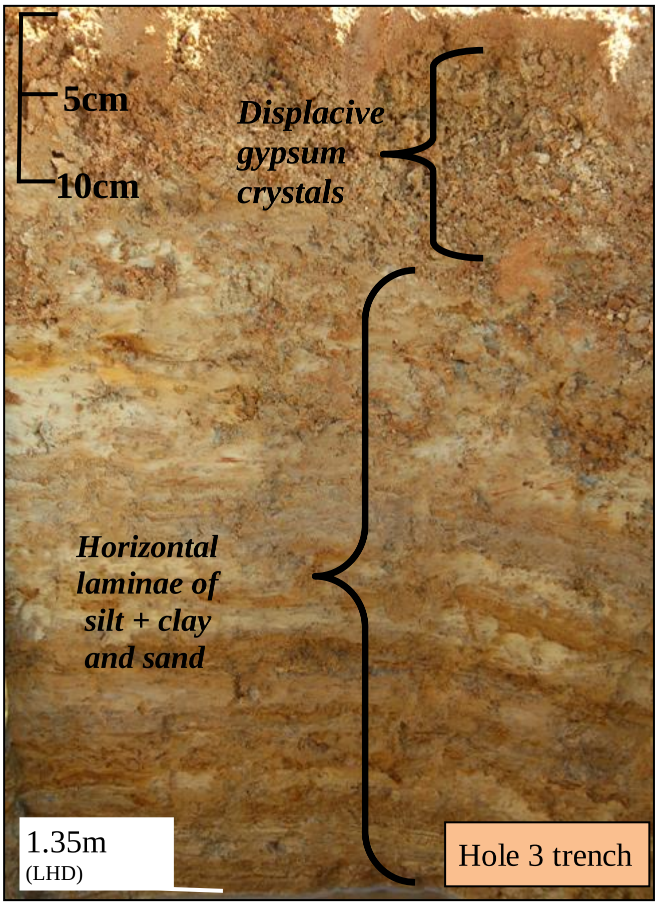

Figure 4.8: Hole 3 displays gypsum growth in the surface sand with laminae of silt, clay and sand below.

The laminae become increasingly dominated by sand through holes 1 to 17 (see Figure 4.4 for hole locations) as the silt and clay content becomes confined to discontinuous lenses within the sandy laminae. The reduction in thickness and incidence of silt and clay strata towards the elongate landform is illustrated by the grain size frequency graphs of hole 3 and hole 18 (Figure 4.9, Figure 4.10, see Figure 4.4 for hole locations). This can also be seen by comparing the sediment in the hole 3 trench seen in Figure 4.8 with that of holes 18 and 17 at the southern extent of the embayment as seen in Figure 4.11.

A pebble unit in a gray sand matrix (~0.2m thick) continues below the laminated sediments from holes 13 and 14 to hole 1 on the lake floor at a height of around 1m (LHD, see stratigraphic logs Appendix 4.4 for details) and follows the dip to the south This unit appears to be discontinuous across the embayment as only pools of the same unit are found further to the south of hole 1.

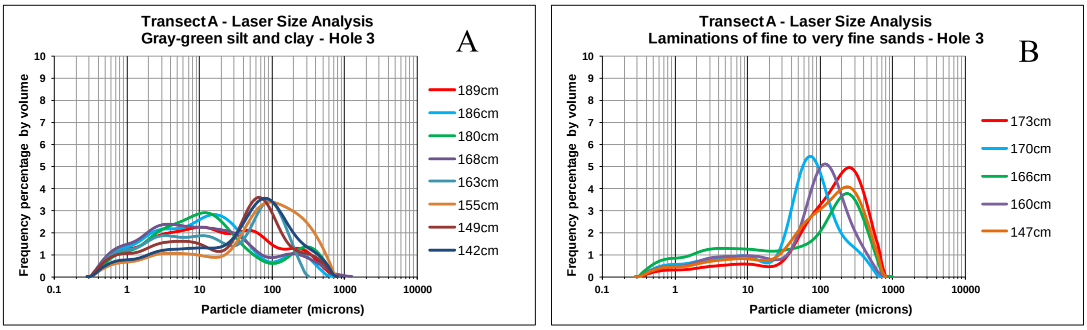

Figure 4.9: Grain size frequencies A) hole 3 silt and clay laminae, B) hole 3 sand laminae.

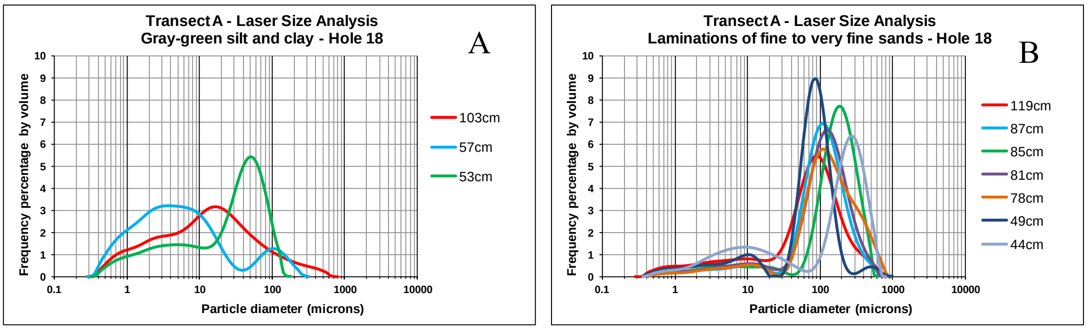

Figure 4.10: Grain size frequencies A) hole 18 silt and clay laminae, B) hole 18 sand laminae.

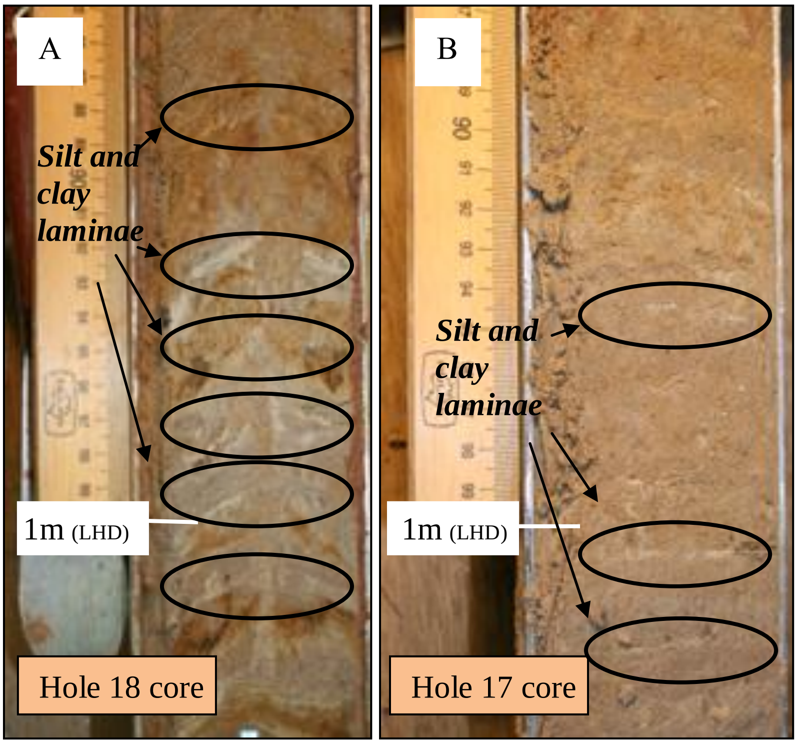

Figure 4.11: Reduced thickness and prevalence of silt and clay laminae from hole 18(A) to hole 17(B). Note the sediment in core 18 is compacted towards the edges of the core.

A basal unit of compact oxidised silts and sandy silts runs under the embayment from hole 13 across the lake floor and beneath the elongate bench that borders the embayment in the south at hole 16 (see Figure 4.4 for hole locations). The compact sediments appear to consist of massive beds of silt, clay and sand with occasional discontinuous beds of sand, granules and pebbles (Figure 4.13, see stratigraphic log Appendix 4.4 for details). The unit consists of more than 80% silt and clay at hole 13 but this varies to less than 50% across the embayment (Appendix 4.3). The unit is for the most part highly oxidised as is seen in Figure 4.12, but at hole 13 a thin layer of this unit consists of compact gray-green (reduced) silts which are also found at hole 15 (see stratigraphic logs Appendix 4.4 for details). The upper horizon for this unit dips towards the south and the maximum thickness of this unit at around 0.5m is found beneath the embayment floor sediments with well rounded pebbles at the base (b-axis 55mm).

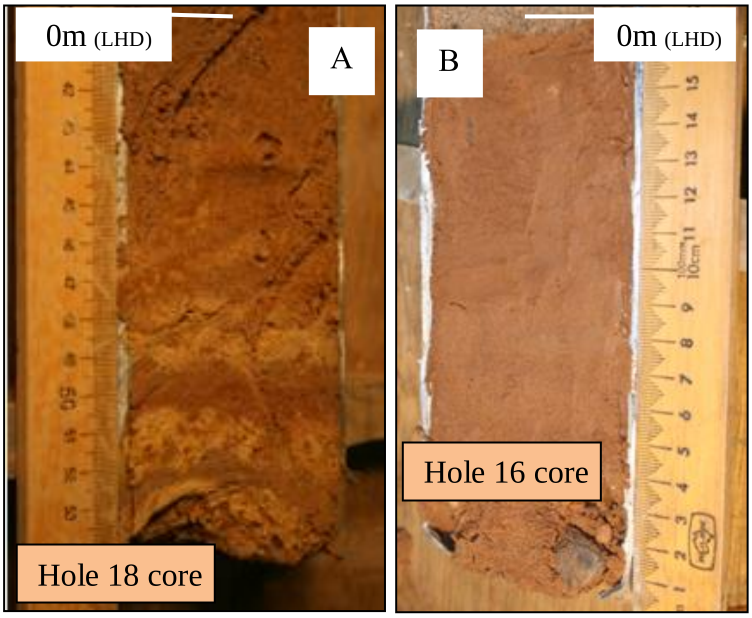

Figure 4.12: A) Compact lacustrine sand and silt in the basal unit of hole 18 and B) compact silt, clay and sand fining up in hole 16 with pebble at the base.

Southern margin of the embayment

The southern margin of the embayment is formed by an elevated and extended sandy knoll with a patchy covering of pebbles and granules (Figure 4.13). The elongate landform stretches across the lake floor from the western margin of the embayment appearing to be a raised beach or spit (Figure 4.4). At hole 16 the elongate landform sits 1m above the surrounding lake floor at an elevation of 3.04m (LHD).

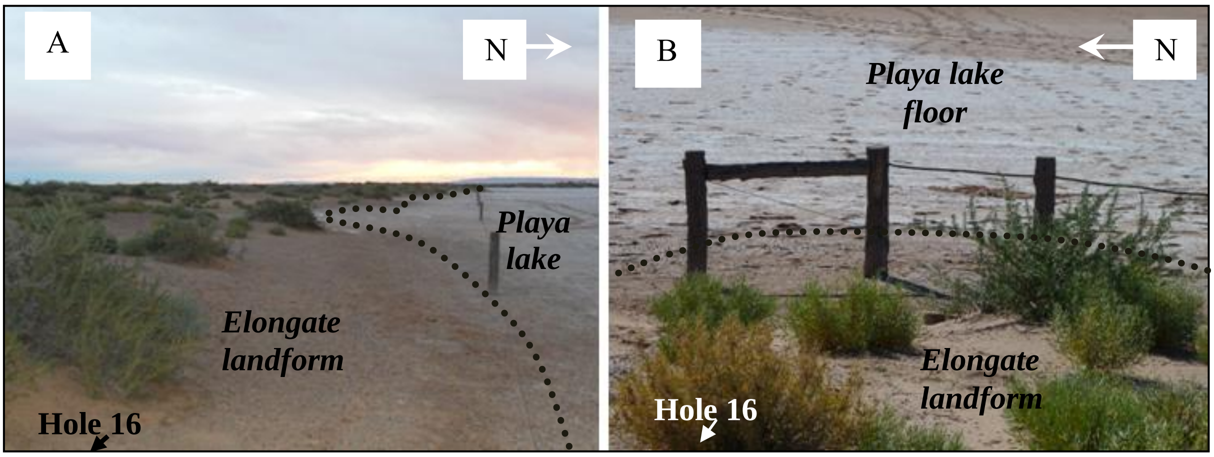

Figure 4.13 View of elongate landform raised above the lake floor A) northern side viewed from the point, B) view of tip and lake floor from hole 16.

Figure 4.14: Down core view of the gravel bar below surface sands at hole 16.

Hole 16 is a 3.17m core taken along the apex just before the tip of the landform (Figure 4.4, Figure 4.13). At around 0.9m above the lake floor a bar of sub-angular pebbles (60mm b-axis), granules and sands 0.5m thick is located (Figure 4.14). The pebble bar overlies several sequences of generally massive fine and medium to coarse-grained sands with floating pebbles and scattered concentrations of granules. The sediments of the elongate landform fine up considerably between 1.3-1.8m (AHD) and carbonate concretions have developed in the sediment characteristics are similar to the fine sands and silt of the lake floor sediments.

The sands that make up this elongate unit appear to be a related but different unit to the laminated unit that surround it in the lake floor strata (Figure 4.15). The sediments in hole 16 contain relatively few silt lenses and are generally coarser than the lake floor strata laminae (Figure 4.15, Figure 4.17, Figure 4.18). The sediments below 1m (LHD) in hole 16 consist of massive beds about 0.5m thick of fine and medium to coarse-grained sands that contain rip-up clasts as seen in Figure 4.18.

Below the massive sand units in hole 16 about 0.2m of laminated fining up sequences overlie 0.30m of concentrated granules marking an abrupt horizon and the initial stages of deltaic activity at the site. The sediments that make up this structure also contain no evidence of beach ridge detritus or bedding which would indicate lateral accretion in the swash zone. As is the case with the bench at the northern margin of the embayment this landform is interpreted as fluvio-deltaic and is possibly a bar or levee due to its elongate structure. Further investigation into the depositional mode of this unit is warranted however because it resembles a bank attached spit. The hole 16 core ends in the basal layer of thick oxidised silt which is seen in Figure 4.12 (b).

Holes 24 and 19 are located to the south of the elongate unit (Figure 4.4). The units that are found within these holes are similar but not the same as those found at the southern end of the embayment (see stratigraphic logs Appendix 4.4 for details). Within the upper bed of highly oxidised fine to very fine-grained sands hole 24 has a layer of organics very close to the surface and contains a bed of pebbles (b-axis 30mm) at a depth of 0.4m that thins out to a single layer at hole 19 (b-axis 40mm). The laminated sand and silt unit continues beneath the oxidised surface units through the holes in a bed about 1.5m thick but whilst hole 24 contains the thick lacustrine basal unit as seen within the embayment (>70% silt & clay - Appendix 4.3) hole 19 contains a massive bed of fine to very fine-grains sands with abundant granules.

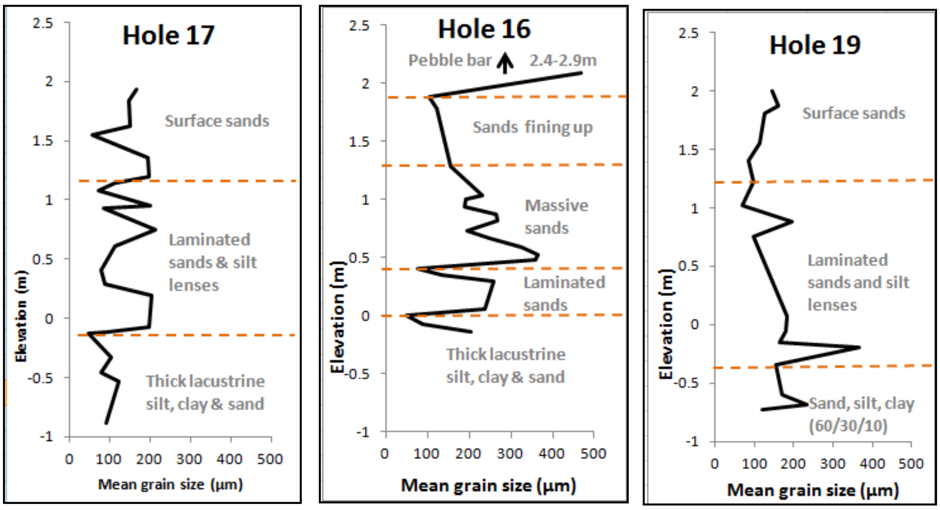

Figure 4.15: Mean grain size a) hole 17, b) hole 16 and c) hole 19.

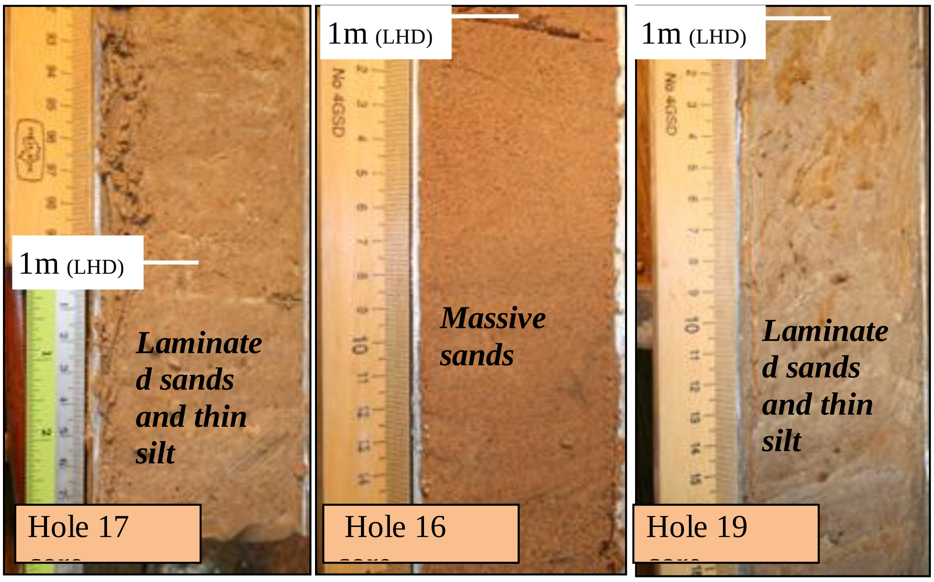

Figure 4.16: Massive and laminated sands from a) hole 17, b) hole 16 and c) hole 19.

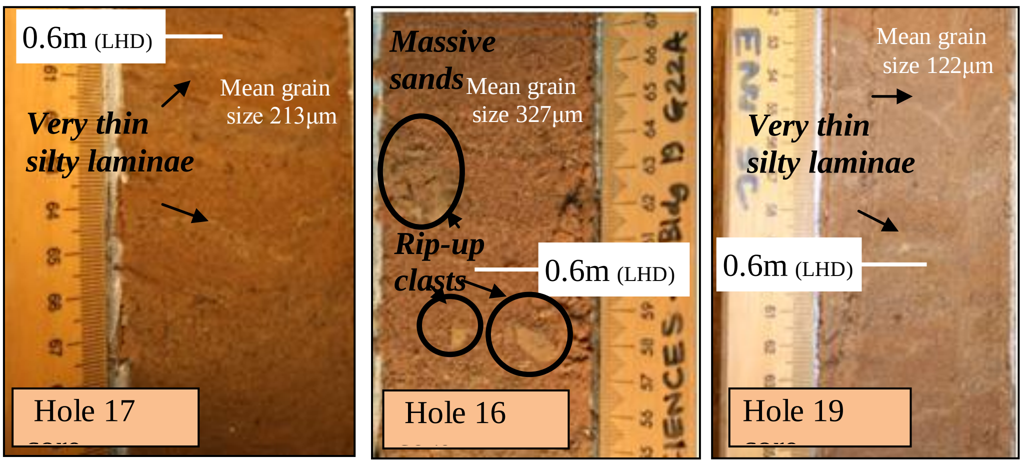

Figure 4.17: Massive and laminated sand in a) hole 17, b) hole 16 and c) hole 19.

Active delta

Hole 27 is situated within the distal reach of the currently active delta of Balcanoona creek (Figure 4.3). Hole 27 is a 0.8m trench opened about 380m south of the elongate landform on the lake floor and consists of horizontal units of weathered silt and very fine-grained sand sequences in which the silt and clay contents fluctuate up to around 85% (- Appendix 4.3Figure 4.18).

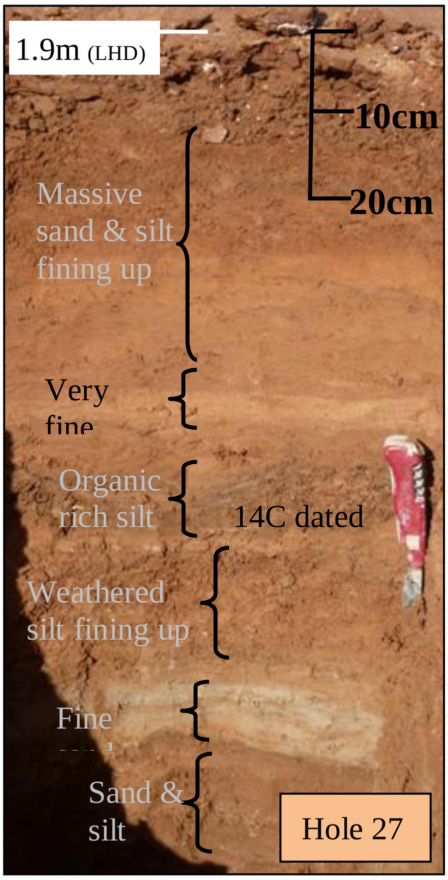

Figure 4.18: High silts content and weathered appearance of sediments in hole 27.

Transect A summary

Figure 4.19 shows an abridged version of the sedimentary units that cross the the northern and southern boundaries of the embayment and the embayment floor. Each unit denotes a different environment of deposition at the study site and the transect indicates that the embayment has made at least two transitions from lacustrine to deltaic and at least one transition more recently to that of an ephemeral playa. The extent of post depositional modification or erosion of each of the units is unknown except for the uppermost units that display significant erosion and redistribution.

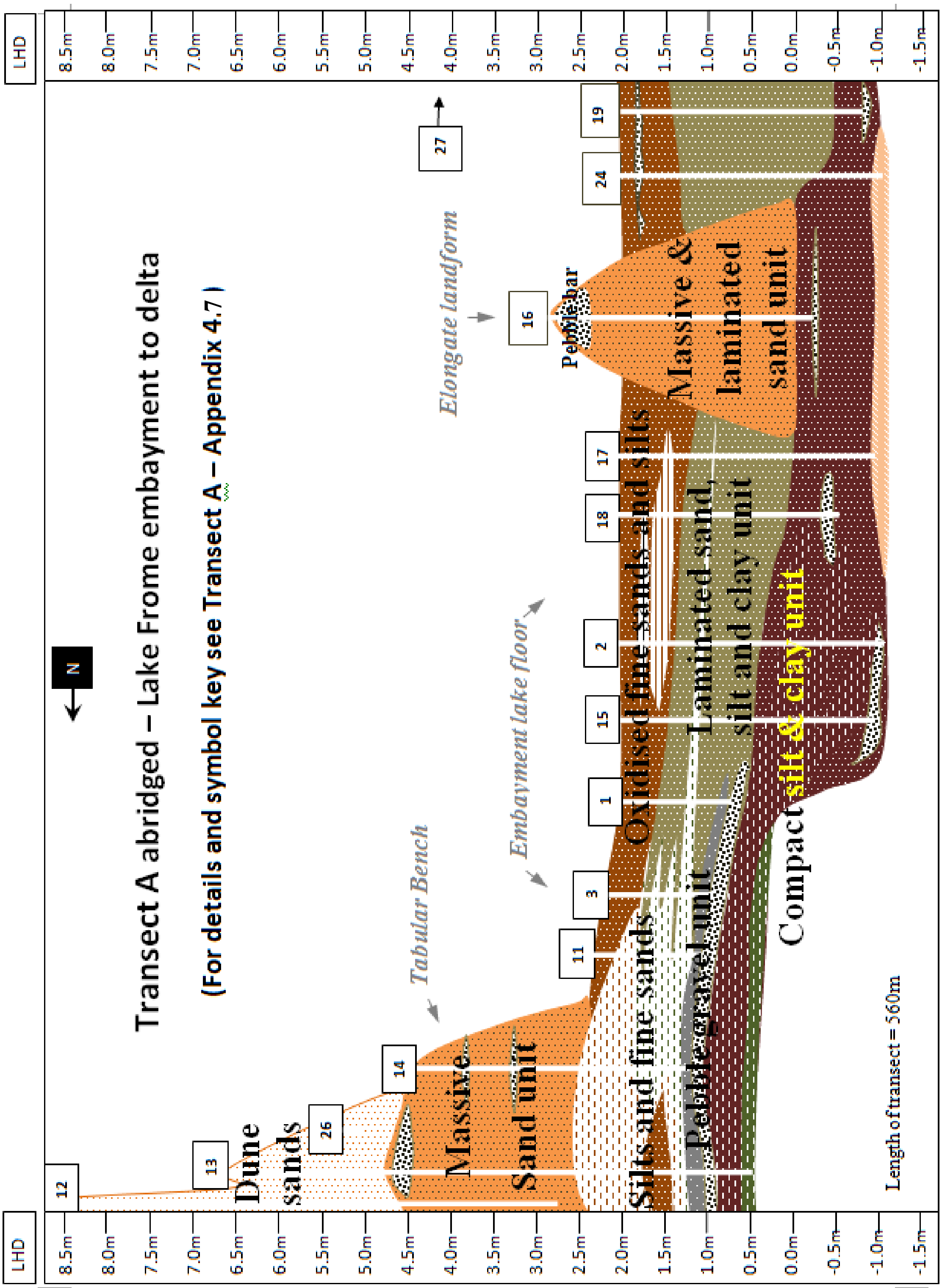

Figure 4.19: Transect A abridged.

4.3.2 Transect B

Transect B west - Remnant dunes

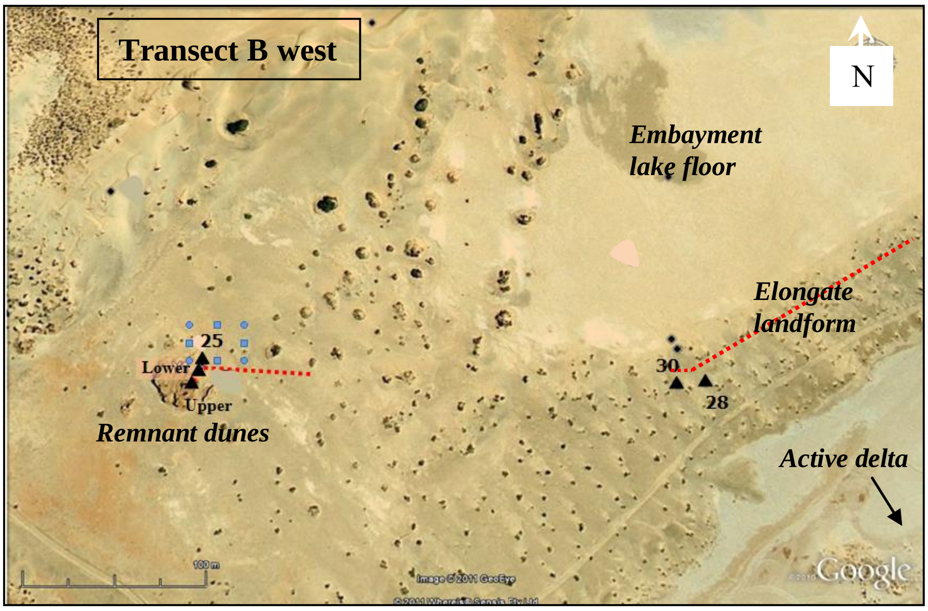

Figure 4.20: Locations of trench and core holes in Transect B west.
(Image from Google Earth 2011)

Figure 4.21: Remnant dunes located along the western shoreline.

A series of weakly cemented and partially consolidated remnant dunes are located along the western shoreline of the embayment (Figure 4.20, Figure 4.21). The largest of the dunes rises to an elevation of 6.84m LHD and has plants growing along its upper surface (Figure 4.22). Sediment samples were taken from the upper and lower wall (which was also sampled for TL) and also from the ground level remains of the dune in hole 25 (Figure 4.20, Figure 4.22).

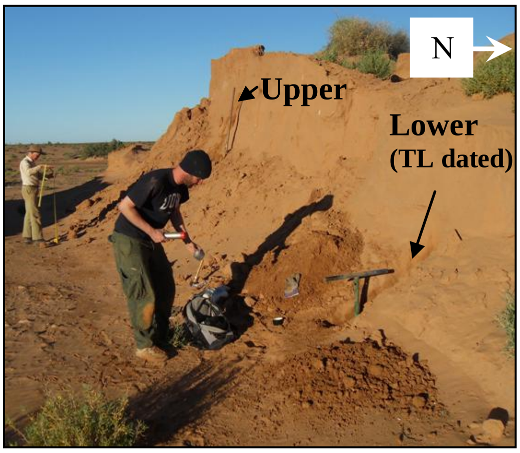

Figure 4.22: The upper and lower remnant dune sites.

The highly oxidised red sands that form the dune are massive with no bedding structures visible from the side profile. Samples taken from along the upper wall consists of well sorted very fine-grained sand with 26% silt and clay (4.3). The sands in the remnant dune coarsen to fine-grained sands towards the base at 3.7m (LHD) and below the surface at 3.36m (LHD) the sediment coarsens again containing granule sized gravel interpreted to be fluvio deltaic in origin. Beneath the deposit of granules a palaeosol with signs of bioturbation has developed in a thin unit of fine-grained sand which overlies medium-grained sand containing granules and pebbles with a carbonate crust which is once again interpreted as fluvial in origin. This pebble bed also continues northeast under hole 25 at a similar elevation (~3.3m LHD, see stratigraphic logs Appendix 4.5 for details, also Figure 4.23).

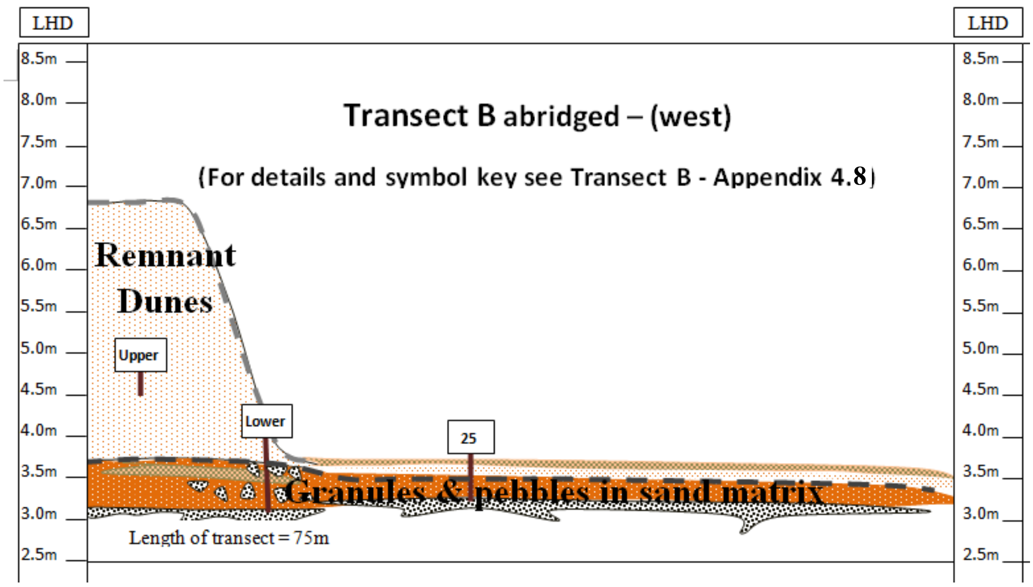

Figure 4.23: Transect B abridged – west

Transect B west summary

Figure 4.23 shows the sedimentary units that lie to the west of the embayment from the remnant dunes down to 3m (LHD). This section shows a transition from a fluvial or fluvio-deltaic unit to a unit that demonstrates subareal modification and aeolian deposition.

Transect B east – southern margin of the embayment

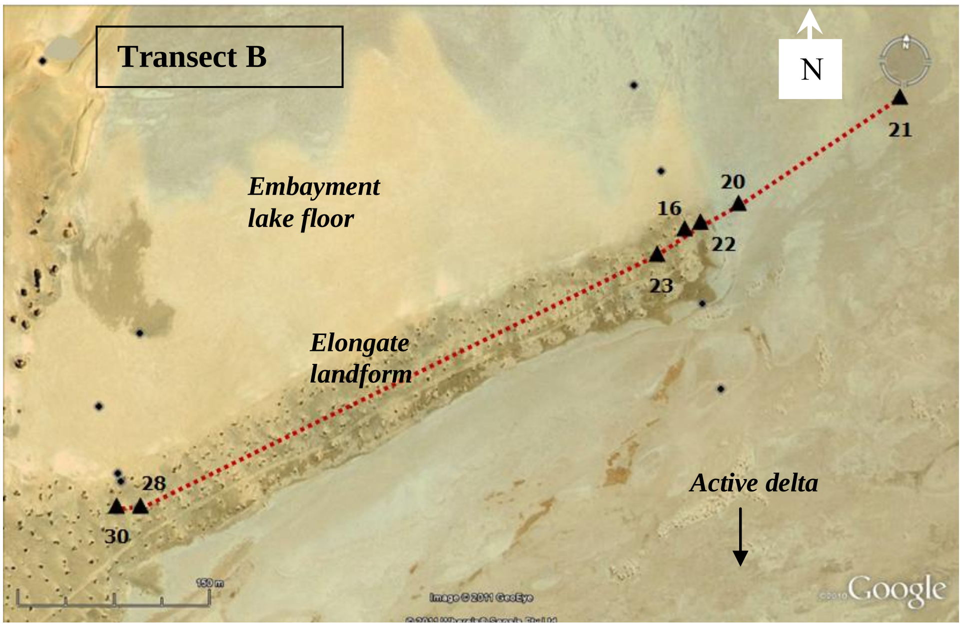

Figure 4.24: Locations of trench and core holes in Transect B east.
(Image from Google Earth 2011)

Holes 30 and 28 lie along the elongate landform towards the western shoreline of the embayment (Figure 4.24). Hole 30 is a core taken in three parts to a depth of 3.5m but was also augered between core sections, whereas hole 28 is a trench sunk to a depth of 1.4m. Massive and moderately well sorted (0.7 θ - Appendix 4.3) medium to course-grained sands continue down from the surface of both holes 30 and 28, to the base of the trench in hole 28 and in a unit about 1.8m thick in hole 30 (Figure 4.25 (a)). This sand is interpreted as fluvio-deltaic once again because there is no evidence of accretionary bedding nor is there any beach detritus within the sediments, but because of the location of these sands near the surface of this unit it is possible that these sands have been subsequently reworked (discussed further in the next section). The sediments below these massive sands in hole 30 become considerably finer for around 0.5m (fine-grained sand with 50% silt and clay - Appendix 4.3, see stratigraphic logs Appendix 4.5 for details). The remainder of the sediment down-core consists of a 0.5m thick fining-up (317 to 257μm - Appendix

4.3) massive sand unit containing floating granules as seen in Figure 4.25 (b). A band of pebbles (0.45mm b-axis) follows this as seen at the base of the core in Figure 4.25 (b) and then the basal unit in the form of thick partially oxidised lacustrine silt and clay (Figure 4.25c).

Hole 23 is located adjacent to hole 16 on the elongate landform (Figure 4.24). Beneath loose surface sands hole 23 contains a weakly carbonate cemented, 0.35m thick palaeosol (see stratigraphic logs Appendix 4.5 for details). The palaeosol is followed by a 0.2m thick layer of pebbles (2.8mm b-axis) which is shown in Figure 4.26, this pebble layer lies across a similar elevation to the pebble bar found adjacent in hole 16 (Figure 4.14) which is adjacent to hole 23 on the elongate knoll, and also at a similar height to the pebble layer found beneath the remnant dunes in transect B west (Figure 4.23). Massive sand beds underlie the pebble layer in hole 23 to the base of the trench at 2.12m (AHD), only interrupted by a few laminae of highly oxidised sands or sands darkened by organic matter (see stratigraphic logs Appendix 4.5 for details).

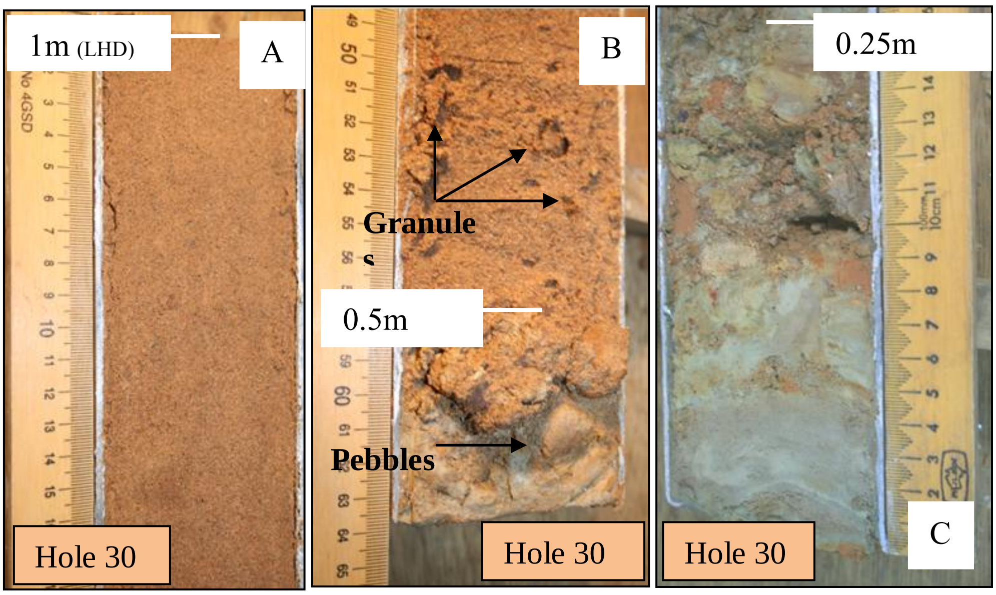

Figure 4.25: Hole 30 A) massive sands fining up to the top of the core B) massive poorly sorted sands with granules and pebbles at the base C) basal unit of thick silt and clay.

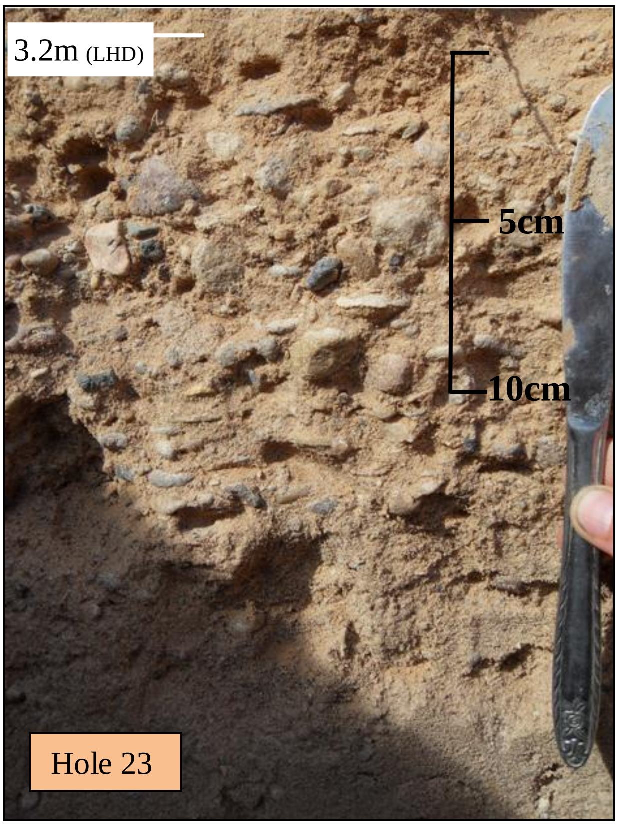

Figure 4.26: Bar of pebbles in hole 23.

Hole 16 is located at the tip of the elongate unit and is discussed above in Section 4.3.1, southern margin of the embayment.

Holes 22, 20 and 21 continue from the tip of the elongate unit across the lake floor towards the east where the elevation of the lake floor is the same as that of the embayment at around 2m (LHD, Figure 4.27). The sedimentary units in this section are very similar to those found within the southern end of the embayment lake floor (holes 18 and 17). Massive highly oxidised fine-grained sand with minor silt and clay (>30%, Appendix 4.3) make up the top 1.5m of sediment in these holes, which also contain a few hardened carbonate horizons (~10mm thick, see stratigraphic logs Appendix 4.5 for details). The surface sand unit is followed by the laminated sand, silt and clay unit at around 0.85m thick which consists of lightly oxidised fine to medium-grained sand with occasional silts and pebble beds as seen in Figure 4.27.

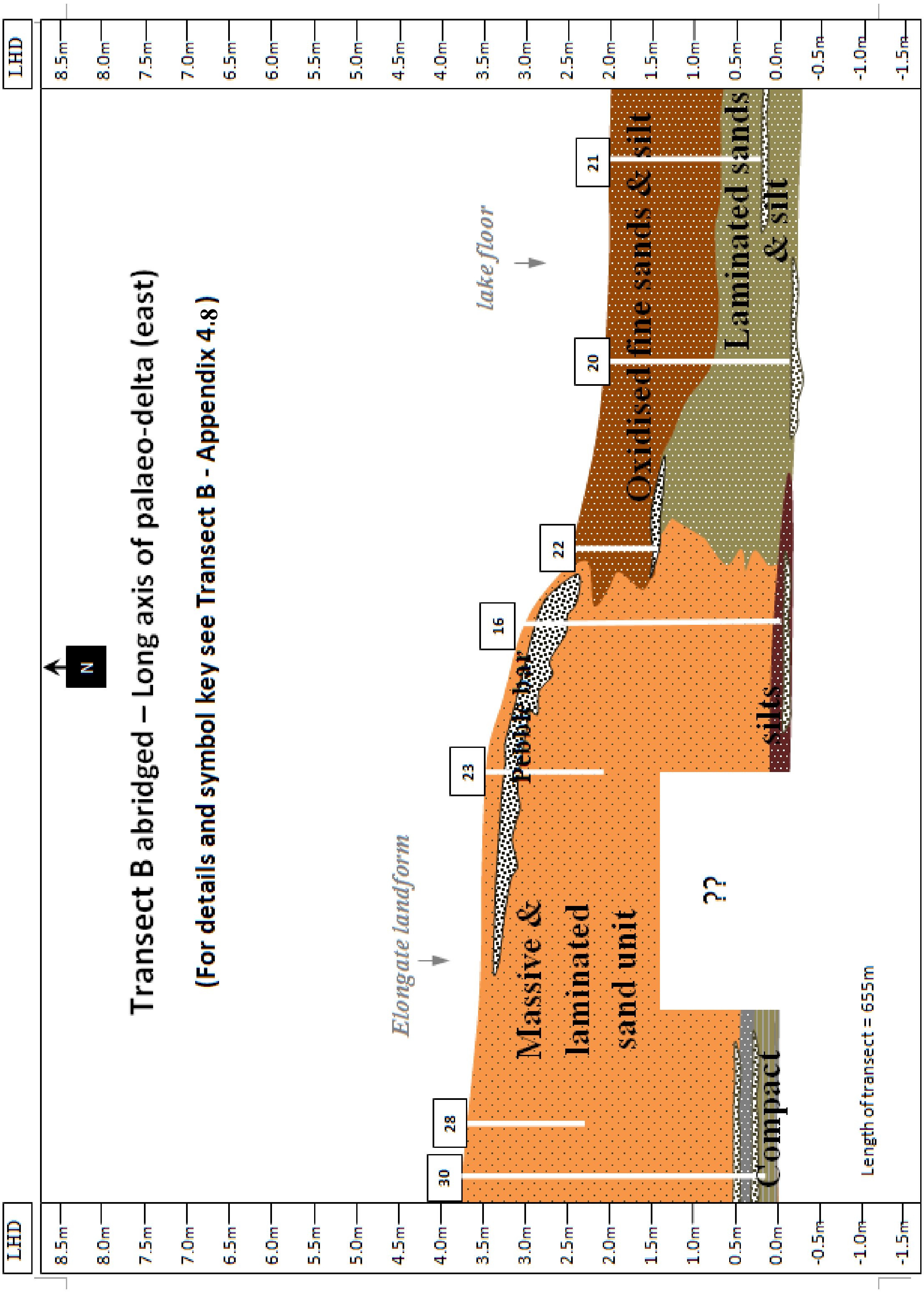

Figure 4.27: Transect B abridged

Transect B east summary

Figure 4.27 shows an abridged version of the sedimentary units that make up the elongate landform which marks the southern margin of the embayment and that of the lake floor to the east. The elongate knoll consists of a series of related units that appear to have been deposited in a fluvial deltaic setting in a short phase of fining up but mostly massive deposits of sediment with one possible lacustrine event or at hiatus in deltiac deposition at this site. Beds of varying grain size coarseness and bedding within the elongate unit mark variations in the depositional energy energy at the site and require further investigation as the the possible mechanisms of their deposition. The presence of the thick deltaic basal unit beneath the elongate landform indicates that a transition from lacustrine to fluvial delta occurred at the contact of the two units and it is possible that the surface sands of the landform also display evidence of the transition to aeolian modification at the site.

4.3.3 Transect C

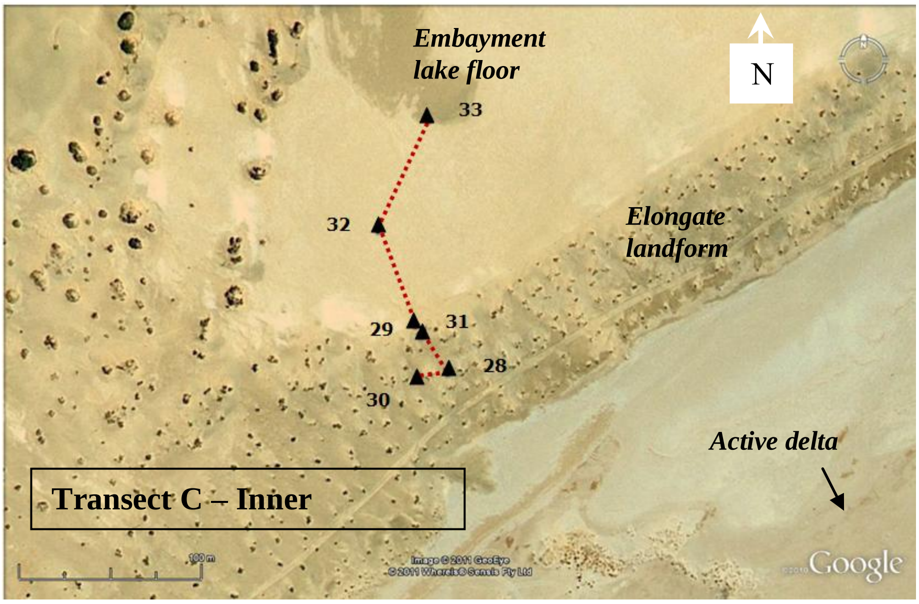

Figure 4.28: Locations of trench and core holes in Transect B east.
(Image from Google Earth 2011)

Transect C encompasses the western margin of the embayment from holes 30 and 28 on the elongate landform to holes 32 and 33 on the lake floor of the inner embayment (Figure 4.28).

Southwest margin of the embayment

The upper profile of holes 30, 28, 31 and 29 display a unit of massive-medium grained sands with occasional horizontally bedded or laminated sand layers (see stratigraphic logs Appendix 4.6 for details). The massive sand unit makes up the entirety of hole 28 which was excavated to a depth of 1.4m and continues to a depth of 1.05m in hole 31. At the base of hole 31 a thin layer (~0.05m) of silt (reduced) lays atop of highly oxidised sands at the base of the hole. This highly oxidised unit continues to the surface of hole 29 which consists of 0.3m of horizontally bedded sand units each displaying a reduced level of oxidisation with depth (see stratigraphic logs Appendix 4.6 for details). Beneath the sand units in hole 29 the sediments consist of a fining-up sequence of silt (75-95% silt and clay - Appendix 4.3) at a thickness of about 0.35m that continues to the base of the hole at 1.5m (LHD).

Lake floor inner embayment

Hole 32 on the lake floor is around 0.4m deep and consists of three layers of fine to very fine-grained sands and silts. The finest sediments with a silt and clay content of 48% are located just below the sands on the surface (Appendix 4.3). Hole 33 is located on a slightly raised bar on the lake floor which is overlain by a surface covering of pebbles (Figure 4.29). A thin 0.05m unit of fine-grained sand similar to hole 32 lies at the surface of this hole with the pebble gravel and beneath that a massive 0.45m thick unit of reduced gray-green silt and clay (86% - Appendix 4.3) that is interpreted as lacustrine or pro-deltaic extends to the base of the hole.

Transect C summary

Transect C displays a series of discontinuous units within the inner embayment. The gray-green silt unit in the embayment surrounded by highly oxidised fine to very fine sands and silts suggests disconformity in the stratigraphy. The reduced sediments may be a residual of the lacustrine/pro-delta silts found below the northern margin at holes 13 and 14 or a residual of the thick silt and clay of the basal unit. Figure 4.30 displays a comparison of the grain size frequencies at hole 33, the pro-delta/lacustrine silts and clays from hole 14 and the thick lacustrine basal unit at hole 13. Figure 4.31 shows an abridged version of the sedimentary units across the inner embayment. The units that cross the lake floor of the inner embayment appear to be discontinuous with what has been interpreted as lacustrine or pro-deltaic silt at the same elevation as the highly oxidised lake floor sands. The units at this site are interpeted as possible lacustrine or pro-deltaic silts that have been modified post deposition to varying degrees and are overlain by aeolian sands.

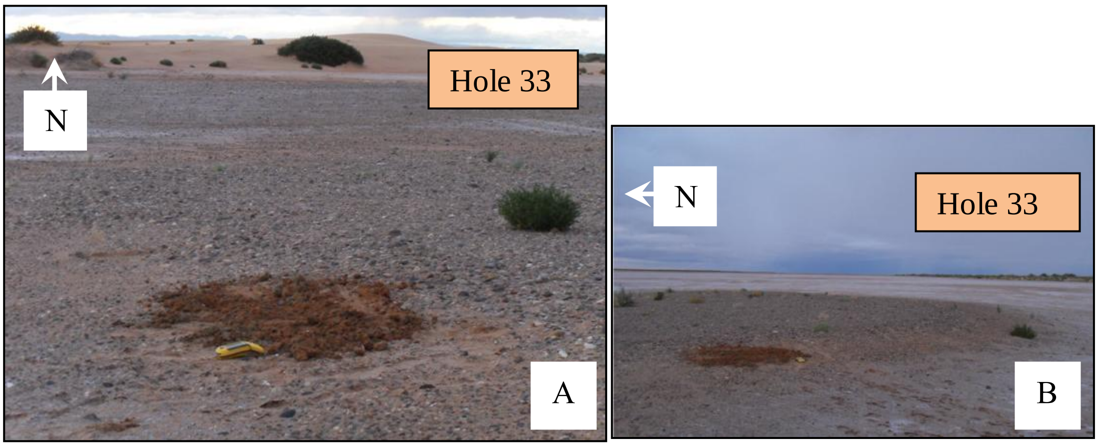

Figure 4.29: Site of hole 33 A) pebbles to ~70mm b-axis (yellow GPS unit is 20cm long) B) view of the low rise bar covered by pebbles on the lake surface.

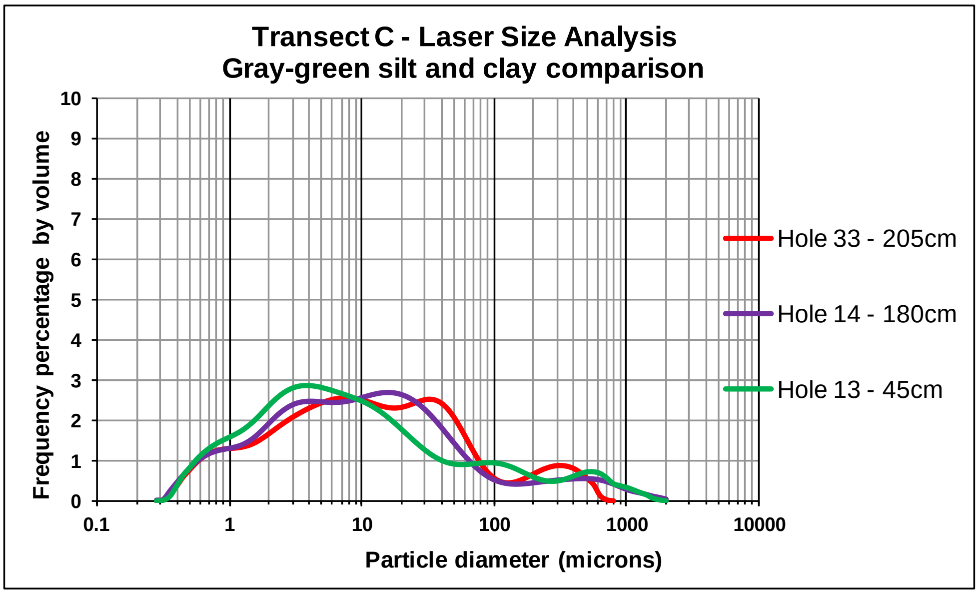

Figure 4.30: Comparison of hole 33 silt and clay with lacustrine/pro-delta silt and clay from hole 14 and basal thick lacustrine unit from hole 13.

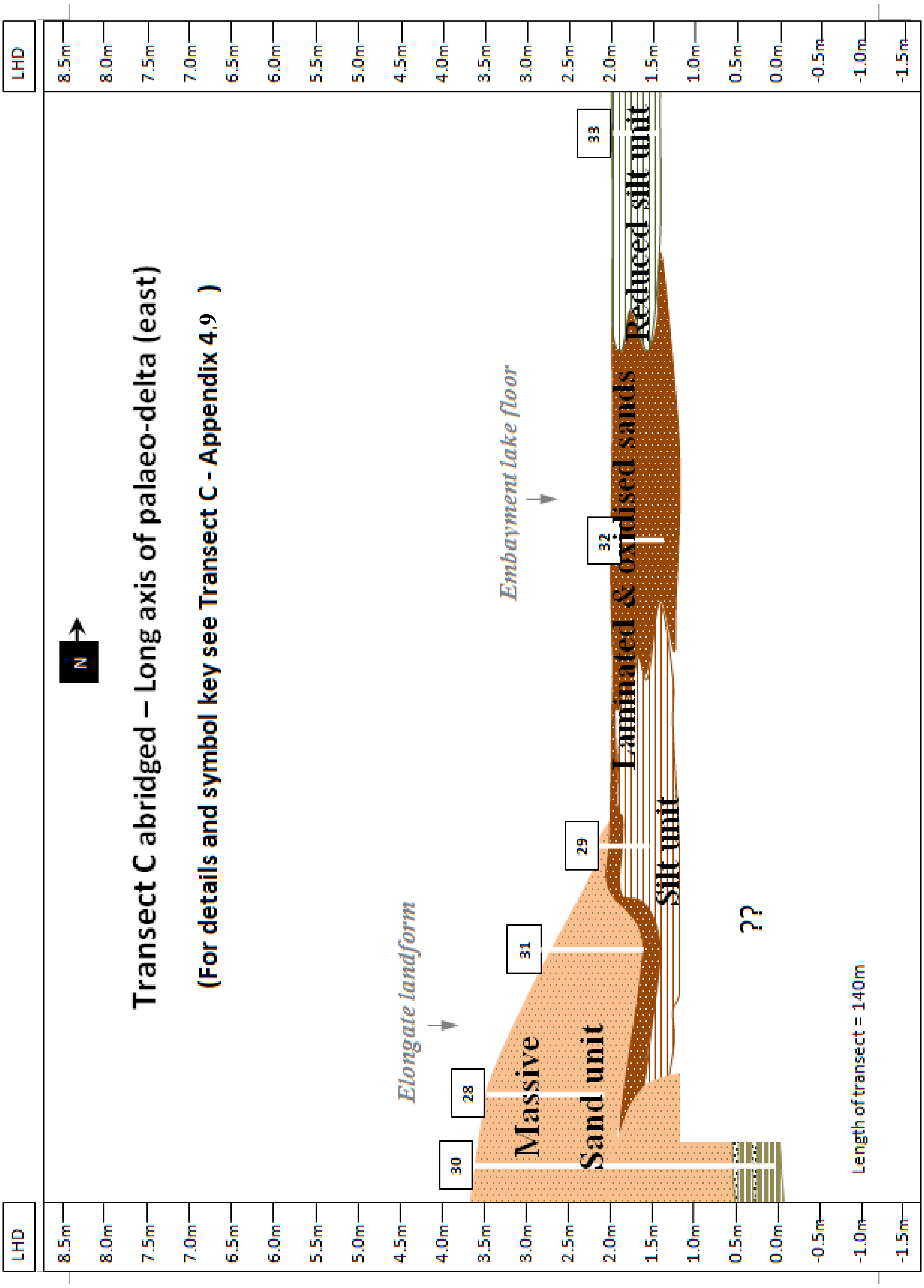

Figure 4.31: Transect C abridged

4.4 Reviewing environments of deposition through grain size analysis

4.4.1 The application and limitations of grain size analysis

It is important to delineate between deltaic, lake and dune landforms because each are proxies of climatic variables and are key to identifying the sequence and magnitude of climate change in the Lake Frome region. The presence of wave deposited beaches at the study site would indicate a climate moister than today, lake water levels and a dominant wind direction; fluvio-deltaic deposition would indicate the height of the water column and also would be evidence of heightened fluvial activity whilst dunes indicate playa conditions as are seen today throughout the area. The depositional mode defines a sedimentary unit and this mode is assigned to a unit of sediment through the analysis of bedding and sediment composition, through geomorphology, by analysing grain size characteristics or by using a combination of those techniques.

At the study site features such as active and remnant dunes were readily identifiable based on their distinctive morphology but making the same distinction between beach ridge and fluvio-deltaic features was not always possible. It was assumed that due to the lack of bedding (as illustrated in Figures 4.32 and 4.33) and lack of beach detritus in the bench and elongate landforms that they were both composed of fluvial sediments that were deposited in a deltaic setting. The morphological characteristics of the units however suggest that the features are a raised shoreline and a spit therefore it was necessary to try to determine the mode of deposition using grain size characteristics.

Through the analysis of grain size distributions of skewness, kurtosis and standard deviation trends can be identified that provide an indication of the likely modes of transport and deposition based on the response of different sized grains to the nature and strength of the flow.

Figure 4.32 Massive sands within hole 30

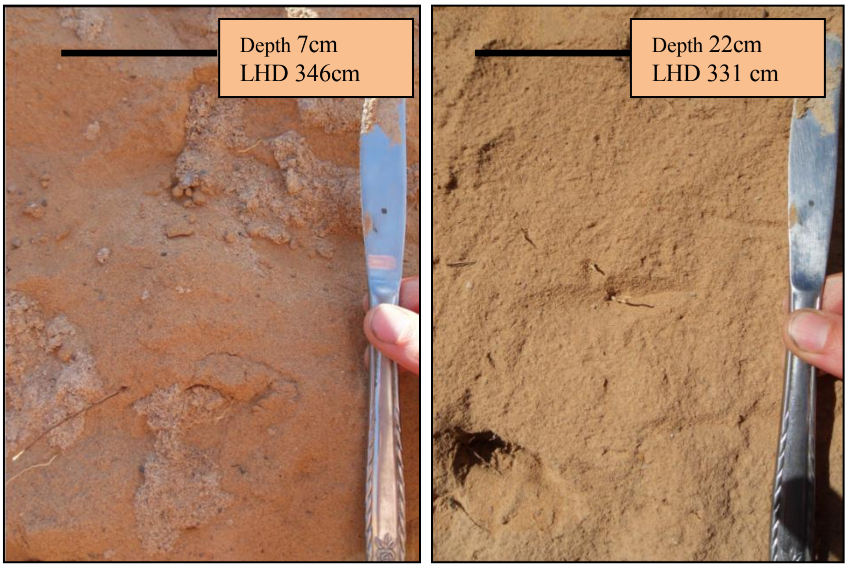

Figure 4.33: Massive sands of hole 23 with concretions and rootlets

4.4.2 Skewness

The skewness of a grain size population is a measure of the predominance of finer or coarser sediment relative to a mean (Boggs 2011). A symmetrical distribution where the majority of grains have similar coarseness with few grains deviating from the mean is un-skewed. Experiments with grain size skewness in the past have found that beach sands from lake or marine settings were more often negatively skewed with greater content of coarser material, whilst sands deposited by fluvial and aeolian flow were more often positively skewed with a greater content of fines (Friedman 1961).

Grain size characteristics from sand built features at the northern and southern extent of the embayment were graphed with respect to the mean grain size and skewness in an attempt to distinguish fluvial from beach sands (Figure 4.34). Deposition in a fluvial environment is unidirectional with sediment being moved under highly variable energy levels whilst shoreline deposited sands are subject to winnowing and generally lower energy variability due to the limitations of wind strength and fetch (Friedman 1961; Schofield et al. 2004). As a result fluvial sands are generally more positively skewed than beach sands.

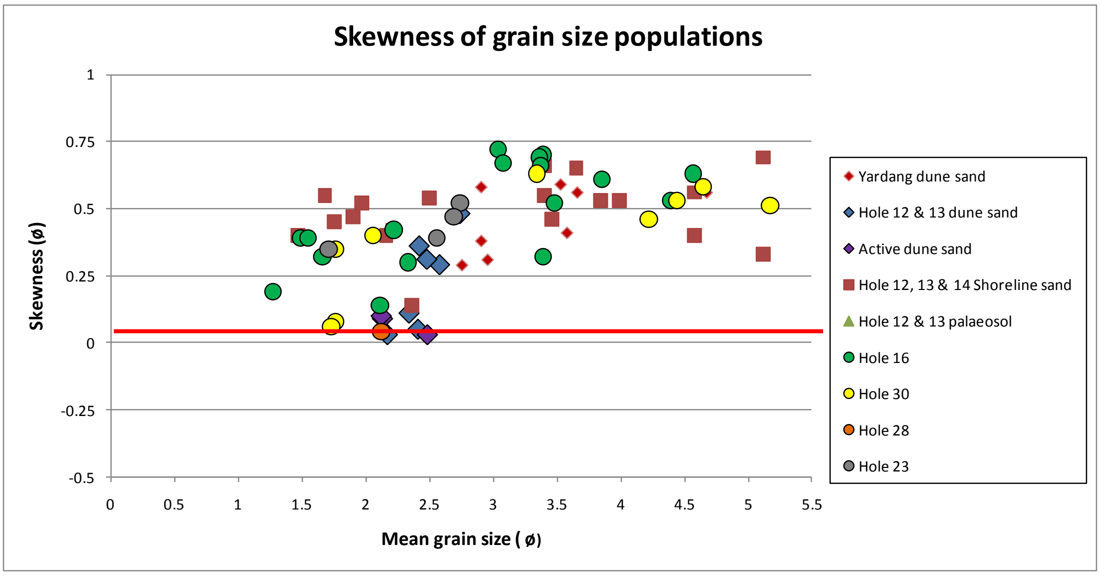

Figure 4.34: Grain size and skewness: Differentiating fluvial and dune sands from beach sands (after Friedman 1961). For location of holes see Figure 4.4.

The grain size skewness graph (Figure 4.34*)* indicates that the majority of sands from shoreline deposits are likely to have been deposited in a fluvial environment. Several samples from hole 30, hole 28 and hole 16 fall close to the border between fluvial and beach deposition along with samples from the active dunes. The study site borders fluvio-deltaic source sediments as evidenced by the present day delta to the south. The proximity of the embayment to an active delta could cause the sands to retain the positive skewness of the parent material even after deposition by longshore drift, as was found to be the case with beach sands deposited near the Rio Grande delta in Texas (Friedman 1961). Alternatively, higher percentages of fine grained material in the shoreline deposits could also be explained by the presence of vegetation along the shoreline ridges and the associated soil fines that vegetation is known to produce. However in addition to finer materials the sands that make up the bench at the northern margin of the embayment at holes 12, 13 and 14 also contain layers of pebbles (to 60mm b-axis) and granules (Figure 4.19, see stratigraphic logs Appendix 4.4 for details) and no detrital beach material nor lateral accretionary bedding which could be expected along wave built shoreline. This information suggest that it is highly likely that the sedimentary unit at the margin of the embayment is fluvio-deltaic so this whole unit will be referred to as the northern palaeodelta from this point forward.

For the most part the sands of the elongate landform have a similar spread of skewness as do the shoreline sands. However, sands from depths 282cm and 288cm (0.81-0.75m LHD hole 30), 274cm (0.3m LHD hole 16) and 30cm (328m LHD hole 28) on the elongate unit plot close to zero with regards to skewness on the grain size skewness graph (Figure 4.31*)* and hence have greater homogeneity of grain size. No evidence was found at any of these horizons of palaeosol development, however in the case of the sample from hole 16 the facies at a depth of 274cm (0.3m LHD) display horizontal laminations of oxidised and non-oxidised sands with granules as well as occasional thin silt lenses. Such facies indicate pulses of deposition and little sediment reworking, none of which are characteristic of well sorted beach materials and once again more likely to be fluvio-deltaic in origin.

4.4.3 Standard Deviation

Graphing grain size sorting or standard deviation and the skewness of sediment grain size is another method of distinguishing fluvial from beach sands. Beach sands through the processes of longshore transport and swash are subject to considerable winnowing out of fine material and usually demonstrate a low standard deviation with regard to grain size as a result (Friedman 1961). Graphing beach sands with fluvial sands on the basis of skewness and standard deviation can resolve the issue of beach sands that have inherited positive skewness and fluvial sands which have inherited negative skewness from their parent material. Friedman (1961) plotted 108 samples of fluvial and beach sands to find that skewness and standard deviation of sediment confined beach sand at less than 0.8ø standard deviation and at less than 1.5ø skewness.

Sediment from the Lake Frome elongate landform and shoreline features were plotted against skewness and standard deviation in an attempt to determine if positively skewed beach sand could be distinguished from fluvial sand parent material on the basis of standard deviation as sand reworked by waves is expected to have a lower standard deviation than fluvial sands. The results show that majority of sediment samples from the elongate landform and shoreline features fall well outside of the beach sand parameters once again with three exceptions (Figure 4.35). Three samples, two horizons from hole 30 and one from hole 28, those with near zero skewness values were the only samples that plotted as possible beach sand on the grain size sorting graph (Figure 4.32). The two samples from hole 30 from depth horizons of 282cm and 288cm (0.81-0.75m AHD) are found within a massive 50cm unit of medium coarse sands (Appendix 4.3). The sands from 282 and 288cm depths were re-analysed to determine the percentage of granule content and the results returned a percentage of less than 1. This information suggests that the sediment from these horizons is in fact very well sorted and may have been subject to winnowing by water currents within the deltaic setting.

Hole 28 is from a depth horizon of 30cm and was recovered from a sediment parcel of massive sands with no bedding structure or change in lithology from the surface to at least a depth of 140cm (Appendix 4.3). The sands from hole 28 depth 30cm

(328m LHD) were re-analysed to determine the percentage of granule content and the results returned a percentage of less than 2 which means that this unit may have been subsequently reworked by beach or aeolian activity.

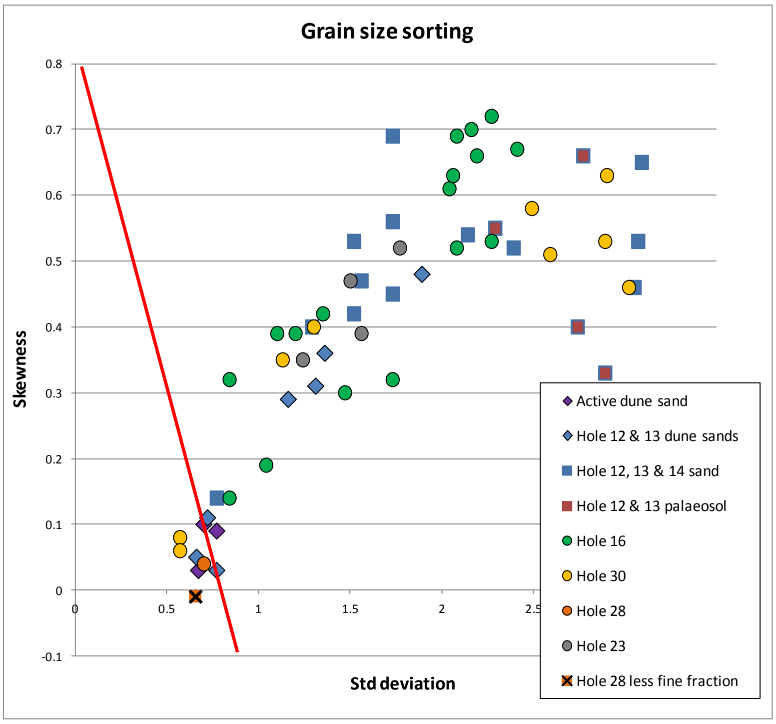

Figure 4.35: Skewness and sorting – differentiation of beach and fluvial sands (after Friedman 1961)

There is a high likelihood that the sediment from hole 28 would contain a higher fine grain size fraction because of its proximity to the surface and windblown dust. The removal of 25% of the finer grain size allows the sediment to be re-analysed without it being skewed by settled out fine materials which can occur near the surface due to vegetative soil formation and aeolian re-distribution. The lack of bedding structure can be best explained by rapid deposition from suspension as could occur at the point of deltaic release into the wide, low gradient and low energy conditions of a large lake body (Boggs 2011). However, the homogeneity and uni-model frequency of the sand at hole 28 could also be explained by the filtering effect of water currents or wind. And as Figure 4.35 (represented by square with black cross) illustrates the sediment from hole 28 plots slightly further from the delineating line and hence with the fine fraction removed the displays a slightly greater propensity to be sand that has been reworked by water or wind.

Although the results from graphing the grain size frequencies do not allow complete resolution of the origin of the sands from hole 28, the grain size properties of the sands from hole 28 and the grain size properties of the active dune sands are clearly very similar (Figure 4.35). The similarities between the sands at hole 28 and the active dunes 250m away to the north suggest that they share a similar source and mode of deposition and it is probably the case that the elongate landform is the parent material and that the active dunes have been blown out from that source.

4.4.4 Grain size distribution and cumulative frequency

Grain size frequency curves are also useful in differentiating between transport mechanisms and hence the environment of deposition (Sun *et al.* 2002). Grain size frequency curves illustrate the different grain size populations that exist in sediment and the degree to which traction, saltation or suspension is responsible for the transport and deposition of that sediment. Bimodal frequencies illustrated by two distinctly separate peaks within the one distribution are the result of transport and deposition by saltation and suspension and are the most common type of frequency curve produced by fluvial sands (Figure 4.36, Sun *et al.* 2002). Grain size frequency curves were constructed for sediment samples collected at Lake Frome in a further attempt to distinguish fluvio-lacustrine, beach and dune sands. The lower sands from holes 12, 13, 14 and 16 demonstrate distinctive bimodal frequencies (Figure 4.37).

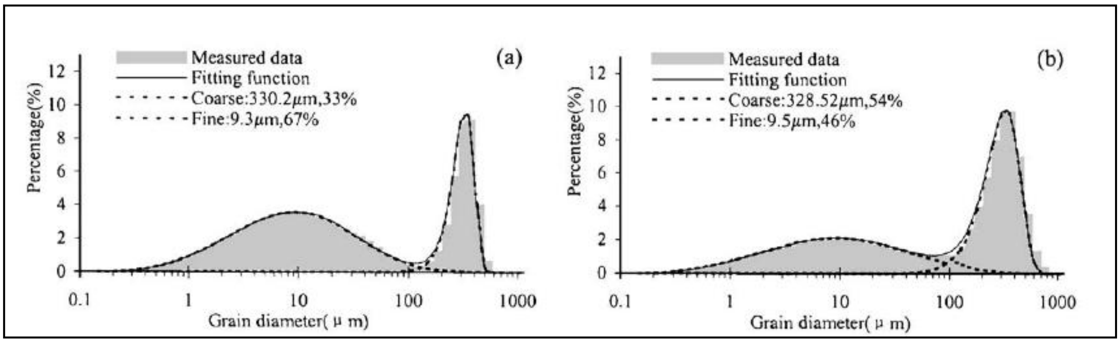

Figure 4.36: Examples of fluvial grain size distributions from Sun *et al.* (2002) a) modern riverbed sand b) sand from Tertiary fluvial deposit.

Sands from the upper horizon of hole 28 and the lower depths of hole 30 however demonstrate a greater unimodal distribution with very little evidence of the suspended fraction as demonstrated in Figure 4.38. Once again the grain size properties of the three horizons on the elongate unit demonstrate properties more similar to the sands from the currently active dunes as seen in Figure 4.39 rather than that of fluvio deltaic sands. This analysis, though not conclusive, demonstrates that whilst the burial depth of the sands in hole 30 make it more likely that the sands have been winnowed during subaqueous deposition, the sands from hole 28 which are close to the surface of the landform could possibly have been winnowed by subareal processes. The sands from hole 28 however are most certainly the parent material or from the same parent material as the dunes that are active today along the western margin of the embayment (see figure 4.3 for the location of the dunes).

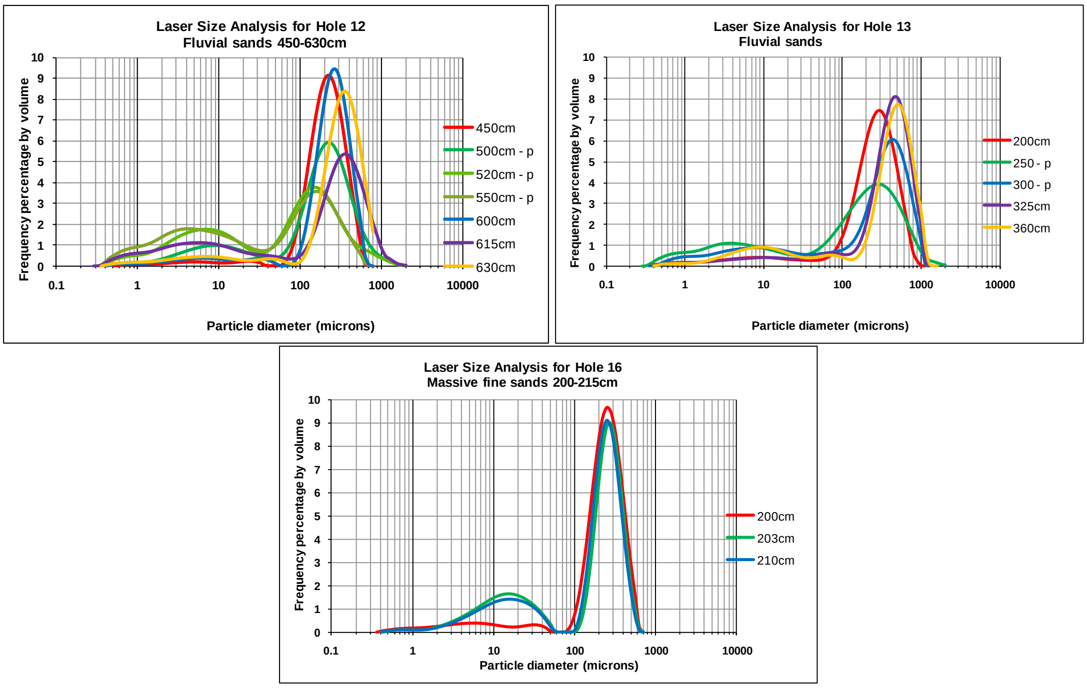

Figure 4.37: The bimodal frequency distributions of shoreline deposits a) hole 12, b) hole 13, c) hole 16.

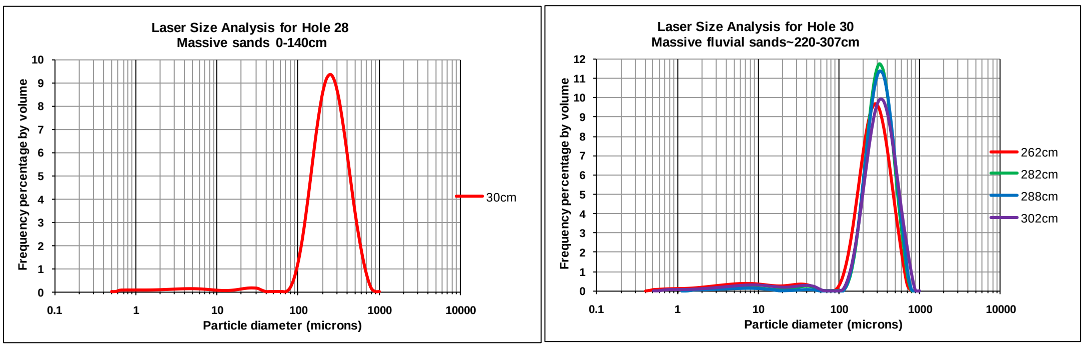

Figure 4.38: The unimodal frequency of sands a) hole 28 and b) hole 30.

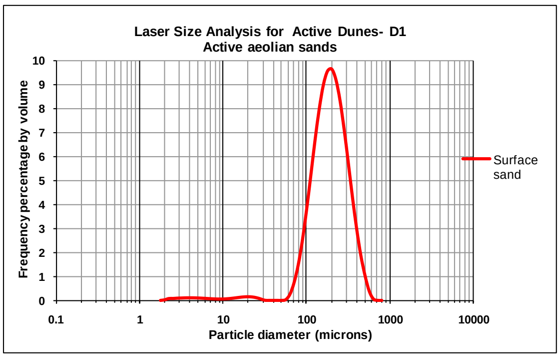

Figure 4.39: The unimodal frequency of sands from the active dunes along the western margin of the embayment.

4.5 X-ray diffraction (XRD) and X-ray fractionation (XRF)

4.5.1 Mineralogy content of Lake Frome sediments

XRD analysis of the sediment from 3 and 18 in the Frome embayment reveals a mineralogy content consistent with a marginal lacustrine to playa lake environment. The halite content in holes 3 and 18 hover between 4 and 10 percent without any change in regard to depth (Figure 4.40). The uniform spread of halite within the holes however is likely to be a result of fluctuating highly saline groundwater levels as well as precipitation of the salts on the lake floor surface. Overall the gypsum content from XRD results reflects a trend that correlates to the concentrations of gypsum observed in the sediment of both 3 and 18 and illustrated on the stratigraphic log to the left of the graphs (Figure 4.40, for full details of stratigraphic log see Appendix 4.4). High concentrations of displacive evaporate gypsum were found very close to the surface in hole 3 and selinite or subaqueously formed gypsum crystals were found in abundance from a depth of around 140cm to 240cm (+0.55 to -0.1 LHD) in hole 18.

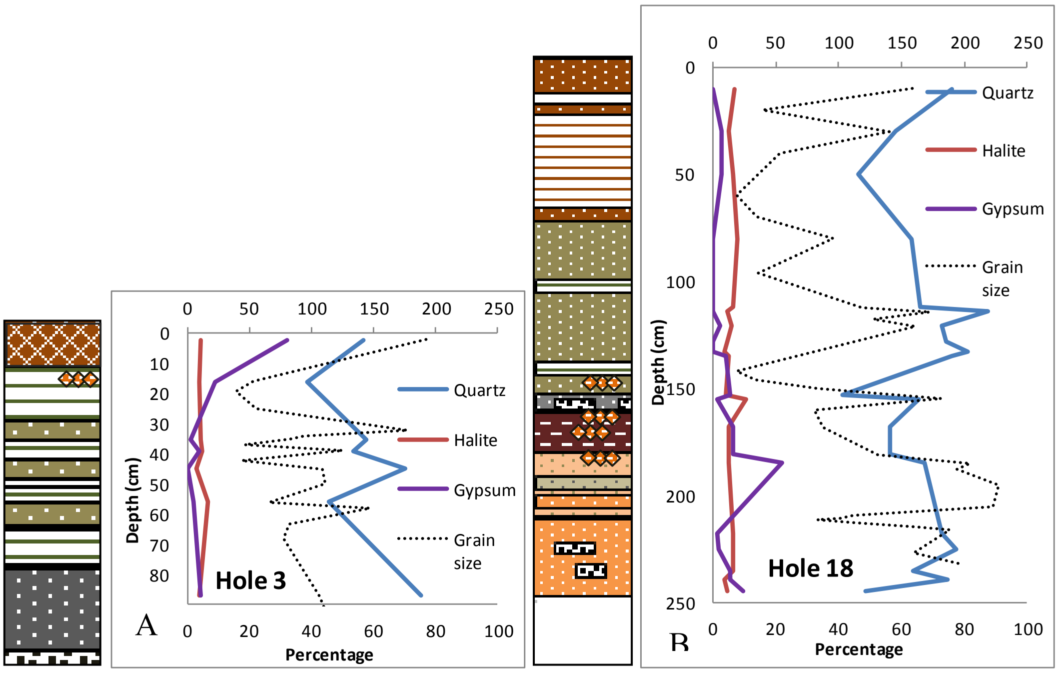

Figure 4.40: Percentages of quartz, halite and gypsum in A) hole 3 & B) hole 18. For key to stratigraphical log on side of graphs see Appendix 4.4.

Carbonate minerals such calcite (often found with the clay mineral palygorskite), aragonite and dolomite (often found with the clay mineral sepiolite) in lacustrine environments are usually of authigenic origin (Webster & Jones 1994). The carbonate minerals in the sediment of hole 3 are mostly composed of calcite whilst in hole 18 there is a higher prevalence of dolomite and aragonite within the sediment (Figure 4.41a & e). The peaks in carbonate content in both 3 and 18 occur mainly within finer sediments. The high proportion of calcite in 3 occurs in a clay rich band which suggests an organic source. Whereas the high prevalence of dolomite in 18 could be the result of groundwater movement and near shore precipitation as there is also a high content of selinite within the same basal unit sediment and dolomite is a major component of the lithology of the Flinders Ranges and also within the rock units of the Namba formation underlying the lake.

The presence of feldspar and clay minerals such as illite and kaolinite in lacustrine environments indicate that the sediment has been transported into the lake environment from an outside source usually of metamorphic lithology (Webster & Jones 1994). Hole 3 has distinctive peaks of the feldspar microcline, illite and kaolinite within the upper 100cm (2.0m to 1.0m LHD) and whilst the contents of the sediment from hole 18 contain the same dominant feldspar and clay minerals reflecting the same source of detrital sediments, the percentages are around half that of the values returned in hole 3 for the same minerals (Figure 4.41c, d, g, h).

4.5.2 Trace elements in Lake Frome sediments

Trace element results for holes 3 and 18 along with the major elements analysis carried out for TL samples revealed that the heavy metal content and therefore pollution at the Lake Frome site are at background levels only.

4.6 Chapter summary

This chapter has provided a detailed description of the stratigraphy of the lake floor and raised sedimentary features of the embayment. Whilst the lacustrine units and aeolian features in the embayment provide unmistakable evidence of the nature of their deposition the same cannot be said for the raised features that border the embayment. It was necessary to try to define the mode of deposition for these features however because the mode of their deposition would indicate valuable information of past environments and hence climate change at the study site. Various expressions of grain size parameters where graphed according to past studies by Friedman (1969) and Sun *et al.* (2002) and despite the ambiguities associated with the sediments from those features by a process of elimination it was decided that the sediments from the shoreline features of the embayment were highly likely to be fluvio-deltaic. The exception to this was the upper unit sands from the elongate landform that are likely to have been subject to deflation due to their proximity to the surface. To make discussions around those shoreline features easier to follow in the coming chapters the elongate landform will hence forth be referred to as the elongate palaeodelta and the bench in the north of the embayment will hence forth referred to as the northern palaeodelta.

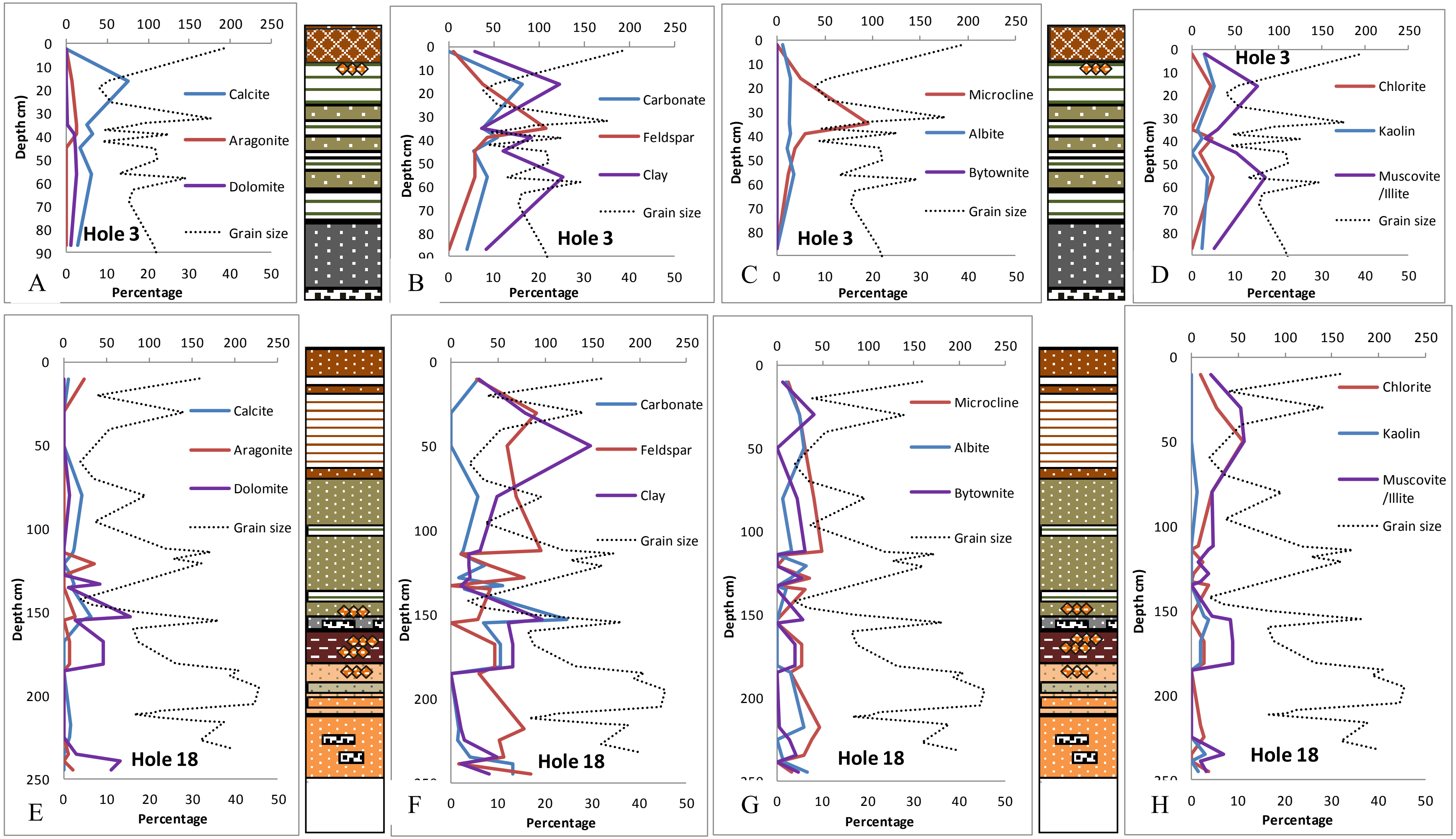

Figure 4.41: Carbonate, feldspar and clay in hole 3 a & b &c & d) and hole 18 e & f &g & h)..

Chapter 5: Chronology and bio-indicators

5.1 Introduction

This study provides a series of thermoluminescence (TL) and amino acid racemisation ages with the addition of one accelerator mass spectrometer ^{14}C age to allow for a chronology to be applied to the depositional sequences identified across the study site. To complement the information obtained from investigating the stratigraphy of the study site the microfossil content of the lake floor sequences is also examined and ecologies from the microfossil populations used to gain an understanding of the duration and salinity of the past lacustrine episodes.

5.2 Methods

5.2.1 Thermoluminescence dating

Quartz rich sediment was collected at the Lake Frome field site from lake floor, deltaic and dune sedimentary units in opaque 7cm pvc tubes along with samples in sealable plastic bags for the measurement of background radiation and water content. Sediment was also collected in 7.5cm diameter plastic cores by the use of a vibracore and quadrapod to sink the tube into the sediment. The cores were cut in a dark room under red light and one half of the core was wrapped in two layers of black plastic to be reopened with the pvc tubes in a dark room under red lighting during the analysis process.

Thermoluminescence (TL) dating and analysis of results were carried out by David Price using a combination of the regeneration and the additive dose methods at the University of Wollongong. TL dating measures energy in the form of trapped electrons which have been relocated within the crystalline lattice structure of a mineral grain by radiation emitted from trace amounts of uranium, thorium and potassium found within sedimentary units (Aitken 1985). During sediment transport exposure to sunlight brings about the release of the relocated electrons in the grains and as such TL dating measures the age of a depositional unit (Shepherd & Price 1990). A portion of the samples collected for background measurement were weighed, dried and weighed again to measure moisture content, ground to a powder like consistency in a tema and moulded into discs with the addition of polyvinyl acetate and heated at 70° Celsius for at least 2 hours. The discs were then analysed by X-ray fractionation (XRF, see section 4.2.4 for details) in order to determine the quantities of potassium and rubidium in each of the samples, whilst the annual radiation dose delivered by uranium and thorium was measured by alpha counting procedure. Sediment from pvc tubes and cores was also prepared and bleached under UV lamp (Phillips MLU 300W) in preparation for the measurement of the paleodose. Whilst the full procedure is described in Shepherd and Price 1990 (omitting the step to calculate ED_s) what follows is a summary of the TL dating process carried out by David Price.

Quartz grains of 90-125μm diameter were separated from the sediment sample by using sieves of appropriate thread. The separated grains are then treated in hydrochloric acid (HCl) and etched in hydrofluoric acid (HF). A quantity of quartz from each of the samples was bleached of natural luminescence by exposure to ultraviolet light for over 24 hours then subjected to fixed increments of ^{90}Sr ß radiation dose. Samples were then heated to 500° C at 5° C per second in order to measure induced TL. TL was measured by an E.M.I. 9635QB photomultiplier fitted with a Chance Pilkington heat filter and a Corning 7-57 blue transmitting filter. The induced TL was then plotted against the irradiation dose to construct a regenerative growth curve. The thermoluminescence of unbleached quartz was measured from several aliquots and the TL output was graphed along with that of the induced TL output for comparison (Appendix 5.1 Glow curve for example for W4453). Natural TL output was then divided by induced TL output and plotted to determine the plateau temperature (Appendix 5.1 Plateau test graph) which is then used as the benchmark temperature for any further analysis.

Portions of unbleached quartz were also subjected to fixed increments of ^{90}Sr ß radiation dose and then heated to 375°C to determine TL output. The mean TL of the natural portions and mean TL of the irradiated natural portions were then plotted on the regenerative growth curve in order to extend the curve from the point of the natural TL output (Appendix 5.2 Growth curve for W4453). For each of the TL samples W4449-4453 the lamp bleached and irradiated and the natural TL which was additionally irradiated fell close or on the growth curves, indicating that TL sensitivity stayed the same for each of the samples. Following these steps each sample portion was subject to irradiation and a second measurement of TL output in order to correct for any variations between aliquots.

The annual radiation dose was measured by finely crushing a portion of the sample sediment which was then applied to a 42mm ZnS scintillation screen and inserted in to an alpha counting cell. Alpha radiation was measured after 21 days with the use of a photomultiplier system calibrated to acceptable laboratory standards. The uranium, thorium potassium, rubidium and moisture content of the samples was used to calculate the annual radiation dose following the procedure described by Aitken (1985, Ch4). The TL age was then calculated for each of the samples by dividing the palaeodose by the annual radiation dose (Table 1).

5.2.2 AMS Radiocarbon dating

Sediment collected at hole 27 from a depth of 0.37m (1.56m AHD) were sieved (150µm sieve) and the organic content of woody remains were separated. The woody remains were submitted to Beta Analytic Inc. for radiocarbon dating (Appendix 5.3)

5.2.3 Microfossil assemblages

Horizons of fine-grained sediment were selected from holes 2, 3, 18, 13 and 27 on the lake floor to be analysed for microfossil content. Between 5 and 25g of sediment was soaked in distilled water for 24 hours to allow the silt and clay content to soften before sieving the sediment with a 125µm sieve to separate the microfossils from finer sediment. Microfossil content was dominated by Ostracoda (phylum; Arthropoda, sub-phylum; Crustacea) which were found to be present in the sediment. Well preserved *Reticypris* sp. valves were separated from the others for amino acid analysis. Valves of all genera present were picked and identified and the number of valves, life stage details and the state of preservation of the valves were noted (Appendix 5.4).

The most prevalent, well preserved and identifiable microfossils present in all sediment samples were the Ostracoda belonging to a few different taxa. *Reticypris* spp., *Diacypris whitei*, *Diacypris dietzi*, *Diacypris compacta*, *Diacypris dictyote*, *Mytilocypris* sp., *Platycypris baueri* and *Australocypris robusta* were identified after De Deckker (1982) and *Diacypris spinosa* was identified after De Deckker (1981) and De Deckker (personal correspondence, 2011).

5.2.4 Amino Acid Racemisation

The tissues of living organisms contain amino acids which are organised into polypeptide chains. Most amino acids (except glycine) contain a single or a number of carbon atoms that display optical properties that rotate polarized light (Blackwell 2001). The tissue of living organisms contain amino acids that almost exclusively rotate polarized light to the left. Production of left rotating amino acids ceases at the same time as protein metabolism ceases, usually at the time of organism death. Following the cessation of protein metabolism the left rotating amino acids begin a gradual (reversible) transformation into right rotating amino acids (Murray-Wallace 1993). The process of transformation from left (L amino acid) to right (D amino acid) amino acids with single carbon centres is called racemisation and in those with a number of carbon atoms it is called epimerization (Murray-Wallace 1993).

Amino acid racemisation (AAR) involves measuring the quantity of both left and right rotating amino acids in order to determine the length of time that has passed since the death of the organism. The rate at which amino acids undergo racemisation is temperature sensitive however, and amino acids recovered from fossils found in warmer climates will exhibit faster racemisation than those from cooler climates (Murray-Wallace 1993).

AAR dating involves measuring the quantities of both L and D amino acids in materials such as ostracoda, mollusc shell, foraminifers, biogenic carbonate sediments and bone to estimate the length of time that has passed since the completion of protein metabolism. Quantities of L and D amino acids are expressed by a ratio of D to L (D/L). D/L ratios from selected amino acids can be calibrated by applying other dating techniques such as radiocarbon or thermoluminescence to the same or adjacent materials or modelled by using Arrhenius parameters (Murray-Wallace *et al.* 2001; Clarke & Murray-Wallace 2006).

Controlled heating experiments can be carried out to bring about accelerated amino acid racemisation, allowing the rate of racemisation to be estimated. If the rate of racemisation proves to be linear when plotted against increasing time and temperature, then the age of fossil remains can be estimated by applying and solving the Arrhenius equation (Blackwell 2001; Clarke & Murray-Wallace 2006). However heating experiments must be conducted on live collected specimens of the same genus or species as those that are being dated because racemisation rates can vary at those levels (Blackwell 2001; Murray-Wallace 1993).

Ostracod valves measure at the millimetre scale; they are made from laminated chitin protein and have a chemical composition of low magnesium calcite (Kaufman 2000; De Deckker 1998). Ostracods are found in a wide variety of aquatic and many terrestrial environments around the world as some only require a very small amount of water in which to live (De Santis *et al*. 2010; Bright & Kaufman 2011). Because of their ability to inhabit a larger variety of aquatic niches, fossil ostracods are often found in environments which support few or no other life forms useful in geochronology, as is the case with the Lake Frome sediments, making their potential for AAR dating high.

Ostracod valves from the genus *Reticypris* were chosen as the subject for amino acid racemisation applied to sediments from Lake Frome. The reason for choosing *Reticypris* above others was because of their abundance in the majority of Lake Frome microfossil assemblages and also because their preservation and therefore robustness was greater than any of the other ostracod genus's present. Sediment was soaked in distilled water for 24 hours to allow the silt and clay content to soften before sieving the sediment with a 125µm sieve to separate the microfossils from finer sediment. Ostracods of the genus *Reticypris* sp. were then separated from the others, further cleaned if necessary and preservation details noted. Only well preserved single and articulated carapaces were chosen for AAR because it was observed in trials on Lake Eyre ostracods that valves with fractures were more likely to disintegrate during preparation.

Reticypris valves were then soaked in 3% H_2O_2 for 2 hours, rinsed three times with double distilled water and air dried. Due to irregular results where reversals in the rate of racemisation occurred down core subsamples of ostracods from selected depths were subject to sterilisation by 12% NaOCl for 24 hours in place of 3% H_2O_2 to determine if interstitial contamination was affecting AAR results. After 24 hours valves were rinsed three times in double distilled water, rinsed in methanol to remove residual NaOCl, rinsed in double distilled water again and left to dry. Valves were dissolved in 5µl of 6mol HCl, vials were flushed with N_2, the samples were hydrolysed for 22 hours at 110°C. Samples were desiccated in a vacuum sealed vessel and rehydrated with 5µl of L-Homoarginine. Amino acid racemisation was measured in the Amino Acid Racemisation laboratory at the University of Wollongong, by reverse phase HPLC liquid chromatograph using an OPT4µl12.M injection and gain set based on the procedure by Kaufman and Manley (1998).

5.3 Thermoluminescence dating

TL ages have been obtained for the study site at Lake Frome for six holes in the embayment (Table 1). The TL ages obtained from Lake Frome were highly consistent in the regard that similar ages were returned from adjacent units and chronological ages were returned for stratified units.

Table 1: TL Ages

TL Number	Field Reference	Depth- (lake surface)	Elevation LHD (m)	Analysis Temp (°C)	Palaeodose (Gy)	Annual Radiation Dose (µGy/yr)	TL Age (ka)
W4406	14/0.5	+2.00	4.0	375	25.8 ± 1.4	2241 ± 62	11.5 ± 0.7
W4407	14/1.2	+1.30	3.3	375	53.1 ± 2.6	3180 ± 63	16.7 ± 0.9
W4449	25/3.7	+1.7	3.7	375	14.6 ± 1.1	2120 ± 61	6.9 ± 0.6
W4450	3/0.35	-0.30	1.7	375	159 ± 10	1970 ± 52	80.8 ± 5.4
W4451	26/0.2	+2.95	6.25	375	11.3 ± 0.9	1829 ± 61	6.2 ± 0.5
W4452	16/2.37	-1.34	0.63	375	104 ± 5	1121 ± 50	92.4 ± 6.2
W4453	30/2.77	-1.14	0.86	375	118 ± 7	1399 ± 52	84.7 ± 5.6

A TL date of 92.4 ka was obtained from a massive sand unit at a depth of 2.4m (0.63 LHD) at hole 16 on the tip of the elongate palaeodelta. Another massive unit of medium coarse sands in hole 30 yielded a date of 84.7 ka at a depth of 2.8m (0.86m LHD). A TL date of 80.8 ka was obtained from a thin (0.05m) layer of very fine sand at a depth of 0.35m (1.7m LHD) in hole 3 in the embayment lake floor. Hole 14 on the northern palaeodelta is a massive unit of poorly sorted fluvio-deltaic sands; two TL ages of 16.7 ka and 11.5 ka were produced from depths of 1.2m (3.3m LHD) and 0.5m (4.0m LHD) respectively within this unit. A TL date of 6.9 ka was obtained from the ground level (3.7m LHD) of one of the remnant dunes located along the western shoreline and similarly hole 26 provided a TL date of 6.2 ka from the dune sequence located above the northern palaeodelta at an elevation of 6.25m LHD.

5.4 Radiocarbon dating

The organic remains from hole 27 were submitted to Beta Analytic Inc. and a conventional radiocarbon age of 2770 $\pm$ 30 BP or 2,860 $\pm$ 30 Cal yrs BP was returned (Appendix 5.3).

5.5 Microfossil assemblages

5.5.1 The microfossil content of Lake Frome sediment

This study provides an account of the diversity, preservation state and ecological indicators from the microfossil taxa found within a range of depths in holes 2, 13, 3, 18 and 27. Ostracoda were the most prevalent microfossil found in any sediment horizon from the Lake Frome embayment but they were not found in every horizon. The ecology and preservation details of ostracod valves can provide useful insight for the palaeoenvironmental reconstruction of lacustrine environments by providing details of the salinity, temperature and the permanency of water bodies (De Deckker 1988).

Additional contents of the sediment horizons included selinite crystals which were found in hole 2 at 3m and in hole18 at depths of 1.4m and 2.4m, and root casts lined with iron oxide were found in hole 3 at 0.42m and in hole 18 at depths of 0.92m and 1.0m (Appendix 5.4). Fragments of unidentified lacustrine faunal remains were found in high numbers at the 1.0m depth horizon in hole 18. A few highly worn charaphyte oogonia were found in both holes 3 and 18 whilst large amounts of muscovite flakes were also found within the sediments of hole 18 between 0.4 and 0.6m depths.

5.5.2 Ostracod species

The Ostracoda found in sediment from the Lake Frome embayment are limited to species from the Cyprididae family and include *Reticypris*, *Diacypris*, *Mytilocypris*, *Platycypris* and *Australocypris*. The ostracod species found in the most numbers throughout the horizons of holes 3 and 18 was *Reticypris* spp. In hole 13 the majority of ostracods were that of *Diacypris spinosa* and in hole 27 *Diacypris dietzi* were the dominant species. Both *Reticypris* spp. and *Diacypris* spp. were found in all of the horizons where ostracods were present but it was only possible to identify *Reticypris spinosa*, *Diacypris whitei*, *Diacypris dietzi*, *Diacypris compacta* and *Diacypris dictyote* to a species level. Each ostracod genera found within the Frome embayment sediment can tolerate a wide range of water salinities, some up to four times that of sea water (seawater being approximately 36‰) and although ostracod eggs can also survive desiccation, the degree of salinity tolerance within the Cyprididae family varies highly amongst species (De Deckker & Geddes 1980; Burne *et al.* 1980; De Deckker 1981; De Deckker 1983b).

The ostracod population from the basal unit is dominated by juvenile *Diacypris spinosa* valves (Figure 5.4). *Diacypris spinosa* has a salinity range of between 4-52‰, but is found most commonly in waters far below 20‰ salinity levels (De Deckker 1981; De Deckker *et al.* 2011). The presence of *D. spinosa* at this horizon suggests an incursion of fresher water into the embayment. A very small number of the highly saline tolerant species *Diacypris whitei* were also found within this horizon but nowhere else in the embayment sediment. According to De Deckker (1992) *Diacypris whitei* is usually found in highly saline lakes where even halophytes do not grow but also has a broad salinity tolerance of 14-195‰. So given that only a very small number were found it is possible that a small area of the lake was saline enough for this species to thrive or their numbers may have only begun to grow following the event that killed *D spinosa*.

Ostracods were found in several horizons from the laminated silt, clay and sand in holes 3 and 18 which the dominant species were *Reticypris* sp. and *Diacypris dietzi* with minor numbers of *Mytilocypris* sp. and a few *Diacypris spinosa* (Figure 5.5, Figure 5.6). However because it wasn't possible to indentify *Reticypris sp* down to a species level, water salinity concentrations cannot be inferred from this dominant population of ostracods. The second most prevalent ostracod found within this unit *Diacypris diezti* is known to have a very broad level of salinity tolerance which extends across 4-141‰ (De Deckker & Geddes 1980).

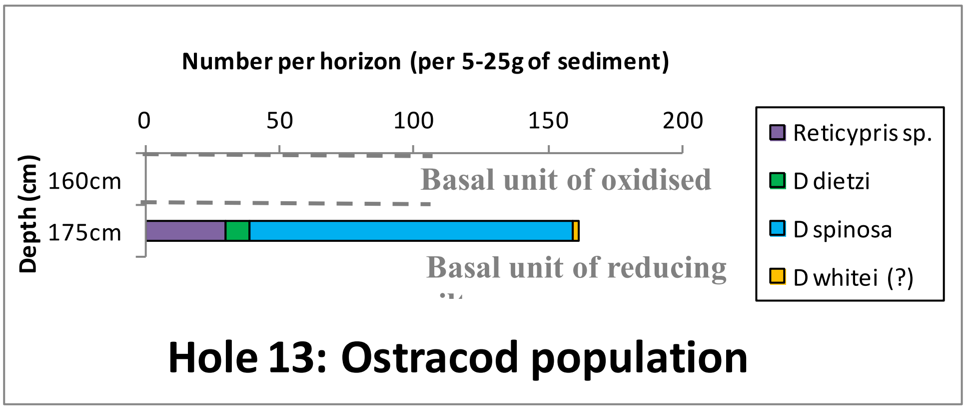

Figure 5.4: Ostracod population of Hole 13 (175cm from lake floor surface = 0.45m LHD).

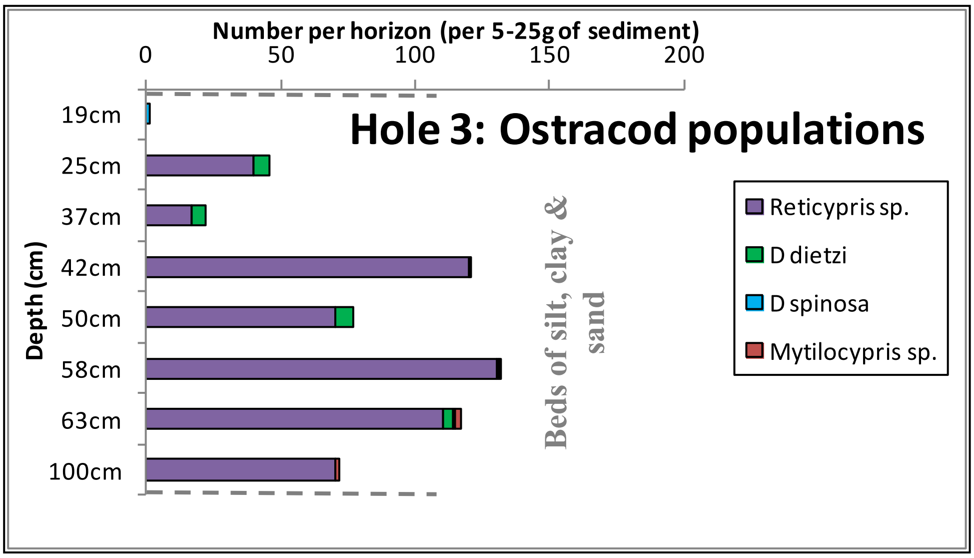

Figure 5.5: Ostracod population of Hole 3 (19cm = 1.85m LHD, 25cm = 1.80m LHD, 37cm = 1.68m LHD, 42cm = 1.63m LHD, 50cm = 1.55m LHD, 58cm = 1.47m LHD, 63cm = 1.42m LHD, and 100cm = 1.05m LHD).

The addition of fragments of what was thought to be *Australocypris robusta* with a tolerance of 7-145‰ within the laminated silt, clay and sand horizons also indicates a wide salinity range (De Deckker 1982). However the presence of a very small number of *Diacypris spinosa* within this unit also indicates that the embayment was receiving enough fresh water at times to provide a habitat for this species as it is unlikely that these fragile valves could be transported far without breaking up.

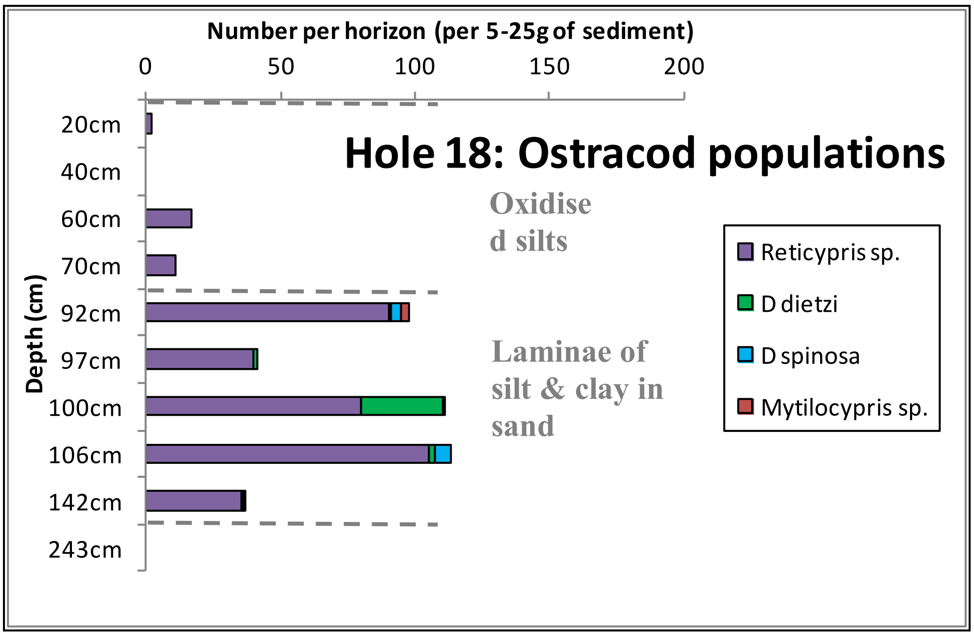

Figure 5.6: Ostracod population of Hole 18 (20cm = 1.80m LHD, 60cm = 1.40m LHD, 70cm = 1.30m LHD, 92cm = 1.07m LHD, 97cm = 1.02m LHD, 100cm = 1m LHD, 106cm = 0.93m LHD, and 142cm = 0.57m LHD).

Only low numbers of *Reticypris* sp. were found in the oxidised silts in the upper lake floor sediments indicating low species diversity and possibly surface water in the lake for only a short duration at this time (Figure 5.6)

The numbers of ostracod valves or carapaces found in hole 27 in the distal portion of the active delta were very low when compared with the units in the embayment, and also reveal a change in population dynamics. The ostracod populations from this unit are dominated by *Diacypris dietzi* with lesser numbers of *Reticypris* sp. and *Platycypris baueri* (Figure 5.7). Neither *Platycypris baueri* nor *Diacypris dietzi* can suggest a great deal about water salinity concentrations they both have a high degree of salinity tolerance however *Platycypris baueri* is usually found in larger numbers at salinities over 70‰ (De Deckker 1982). The presence of *Platycypris baueri* in addition to *Diacypris dietzi* and reduction of *Reticypris* sp. numbers could be an indication of even higher salinity and water level fluctuations. This is because in addition to a high level of salinity tolerance both *Diacypris* and *Platycypris* species are known to be capable of burrowing millimetres down into the sediment to evade desiccating events (De Deckker 1983b).

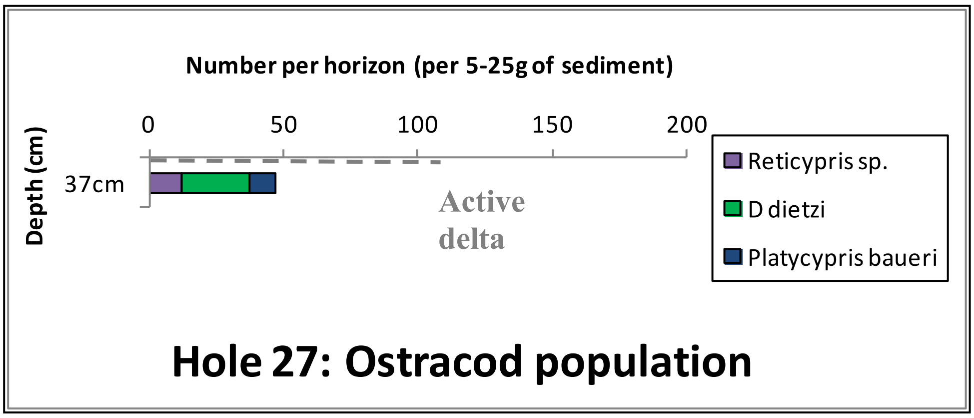

Figure 5.7: Ostracod population of Hole 27 (37cm = 1.55m LHD).

5.5.3 Microfossil preservation and sedimentary characteristics

The general state of the ostracods present in the basal unit and in the laminated silt, clay and sand unit is uniform for *Reticypris* sp. as there were many well preserved specimens in most horizons. *Reticypris* sp. were also the most robust of the ostracods present which may mean that *Reticypris* sp. is better represented in the fossil record than they were in the actual population ecologies of the lake. The more fragile valves of the *Diacypris* species were found in various states of preservation and a few carapaces of *Diacypris dietzi* were found at a depth of 100cm in hole 18 (Figure 5.8), suggesting lower energies or burrowing to escape a fall in water level (De Deckker 1983b). The valves of *Mytilocypris* sp. were often broken and only fragments of *Australocypris robusta* were found.

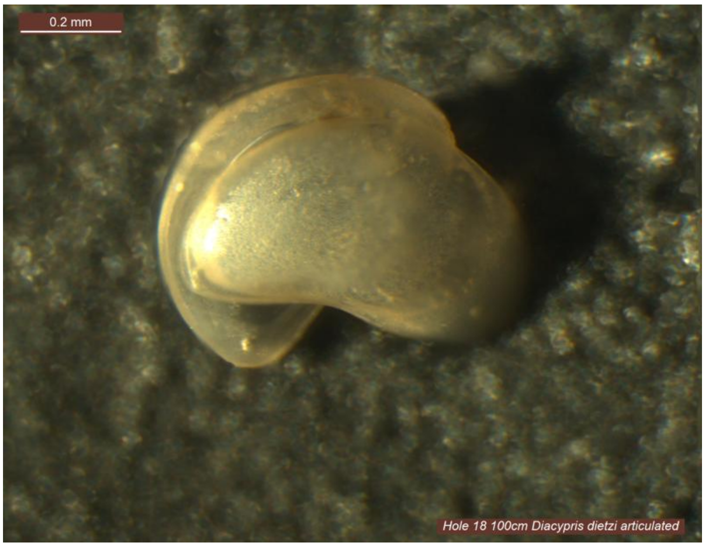

Figure 5.8: Carapace of *Diacypris dietzi* from hole 18 100cm (1m LHD).

A range of juvenile *Diacypris spinosa* occurred in abundance in the sediment from the basal unit, however no adults were identified (Figure 5.9). *D. spinosa* adults measure to at least 0.99mm but the largest of the species found in the sediment from this unit were only around 0.5mm (De Deckker 1981). A population such as this where juveniles of various instars greatly outnumber adults is characteristic of a low energy death assemblage (De Deckker 2002). The death assemblage suggests that a rapid change in environment has occurred after an incursion to the fresher water conditions, this could be a rapid escalation in salinity from the dissolution of surface salts at lake margins or temperature change that has prevented the juveniles from reaching adulthood (De Deckker 2002). Other differences in microfossil preservation and content were noted for the basal unit. A number of *Reticypris* sp. were found with predation bore holes (Figure 5.10). This was not observed in any other horizon or unit indicating the presence of diverse microfossil populations in this horizon. A number of well preserved charophytete oogonia were also found indicating an abundant water plant community (Figure 5.11). A number of root casts were found in the horizons of holes 3 and 18 indicating some form of aquatic plant life in the lake during the deposition of those units.

Figure 5.9: Juvenile *Diacypris spinosa* from hole 13 600cm (175 from lake floor surface = 0.45m LHD).

Figure 5.10: Carapace of *Reticypris* sp. with predation bore hole from hole 13 600cm (175 from lake floor surface = 0.45m LHD).

Figure 5.11: Charaphyte oogonia from hole 13 600cm
(175 from lake floor surface = 0.45m LHD).

As mentioned above the general preservation of the most robust ostracod genus *Reticypris* sp. was good to excellent in the basal unit at hole 13 and the laminated unit within holes 3 and 18. There was slight iron oxide staining in some of the valves but very little observable re-crystallisation and no pyritisation of the calcite valves. A large percentage of *Reticypris* sp. were also found as articulated carapaces. It has been noted by De Deckker (1998) that the presence of intact carapaces indicates a fatal environmental change followed by rapid sedimentation to preserve the carapaces.

Although it wasn't possible to measure the valves to determine that all stages from juvenile to adult were present, a range of juvenile sizes to that of adult *Reticypris* sp valves were found to be present in the same units, indicating that the populations were likely to be life assemblages. This was also the case for *Diacypris dietzi* and *Mytilocypris* sp. where valve sizes ranged from very small juveniles to that of adults. A few *Reticypris* sp. valves were found within the oxidised silts above the laminated sequence in hole 18, but the valves in this sequence were worn compared to those from the units below.

In comparison to the ostracods from the laminated sequences the preservation state of *Reticypris* sp. from hole 27 was not as good despite what the radiocarbon and TL ages suggest is a much more modern sediment, but there were also a lot fewer valves in total. At least one carapace of the very fragile *Platycypris baueri* species was found in this horizon. Intact carapaces of this very thin and fragile valved species indicate fluctuating water conditions because as mentioned previously *P. baueri* is known to burrow millimetres into the sediment to avoid desiccation

5.5.4 Microfossil diversity

The sediment horizon in the basal thick silts provided the most diverse range of microfossils with more than four different ostracod genera and abundant evidence of water plant communities in the form of charophyte oogonia. The presence of charophyte oogonia in the sediment indicates that concentrations of salinity were less than 69‰ as oogonia will only form at lower salinities (Burne *et al*. 1980). Charophytes grow optimally in water levels of less than 2m as the plant requires access to sunlight for photosynthesis which suggests that water levels in the embayment were at around 2m or less at the time (De Deckker 1988). The bore-hole predation marks found on *Reticypris sp.* carapaces are also significant as they demonstrate that a higher order of microfossil diversity was present in the embayment at the time.

A large number of root casts were found in some but not all of the horizons within the laminated silt, clay and sand unit indicating the presence of aquatic plant life, but the small number of charophyte oogonia found in a few horizons were in a much worn state indicating significant reworking and transport had occurred. The ostracod populations from holes 3 display the most diversity from around 0.6m to 1.00m depths whilst in hole 18 the most diversity is found from 0.92m to 0.96m (Figure 5.5, Figure 5.6). Hole 3 still yields two species of ostracods within the 0.25m depth horizon as the silt and clay layers are closer to the surface in the north of the embayment. Only a small number of *Reticypris sp.* were found in the oxidised silts lens that lies within the playa floor sands at depths of 0.2m-0.7m in hole 18 indicating a reduction in diversity following the deposition of the laminated unit.

5.6 Amino Acid Racemisation (AAR)

5.6.1 AAR in ostracod valves from Lake Frome

AAR work on ostracod valves from lacustrine sediment was pioneered by Kaufman (2000; 2003) and has been subsequently utilised by Santis *et al.* (2010), Bright and Kaufman (2011) and Reichert *et al.* (2011) in the reconstruction of palaeothermometry and geochronologies from Quaternary formations in the US and Europe. In order to provide a multi-proxy geochronology for the Lake Frome embayment amino acid racemisation analysis was undertaken using single valves and carapaces of ostracod fossils from the Lake Frome study site. Valves from the ostracod *Reticypris* sp. were recovered from a number of horizons in holes 3 and 18 and from one horizon each in 27 and 13, and both *Reticypris* sp. and *Diacypris* sp. valves were recovered from two depths in Lake Eyre cores to be used as a comparison. Ostracod valves were found mainly in fine silt and clay sediments and were well preserved with many intact carapaces being recovered from the majority of the horizons in Lake Frome (Figure 5.12).

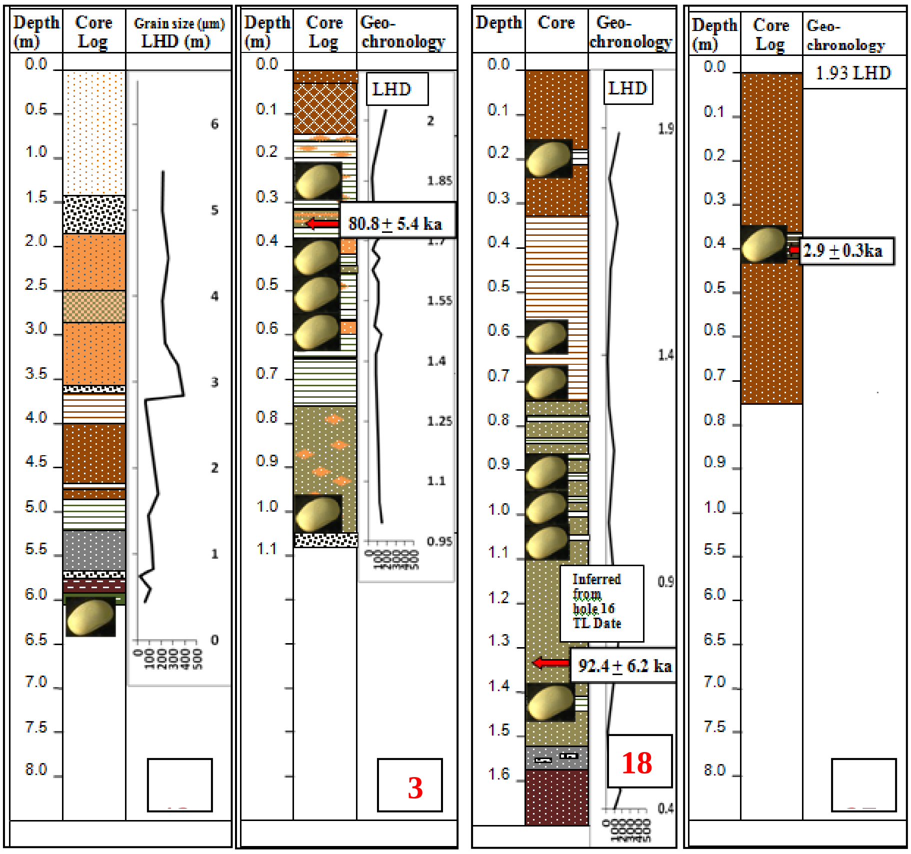

Figure 5.12: Location of ostracod populations within sediment horizons in holes 27, 3 and 18 (For symbol key to sediment see stratigraphic logs Appendix 4.4).

5.6.2 Geochronological application of AAR results

The extraction and application of AAR results from the ostracod valves of Lake Frome and Lake Eyre presented some difficulties. Concentrations of all of the amino acids were very low (L area ~ 20-100 LU) of in the majority of the Lake Frome samples and in all samples only aspartic and glutamic acids were of sufficient peak resolution to be used for further extrapolation. Around 25 samples produced blank runs and about one-third of all the samples were rejected on the basis that L-Glu / L-Ser = <1 (Kaufman 2000) and Serine D/L = < 0.1 (Pleistocene samples only) and a small number were also rejected due to anomalous covariance between aspartic and glutamic D/L values (Kaufman 2000, see Appendix 5.5 for AAR values yellow highlighting denotes rejection due to anomalous covariance). The spread of D/L ratios for each of the horizons were mixed with most displaying relatively tightly clustered populations and a few displaying a large spread of D/L ratios (Figure 5.13).

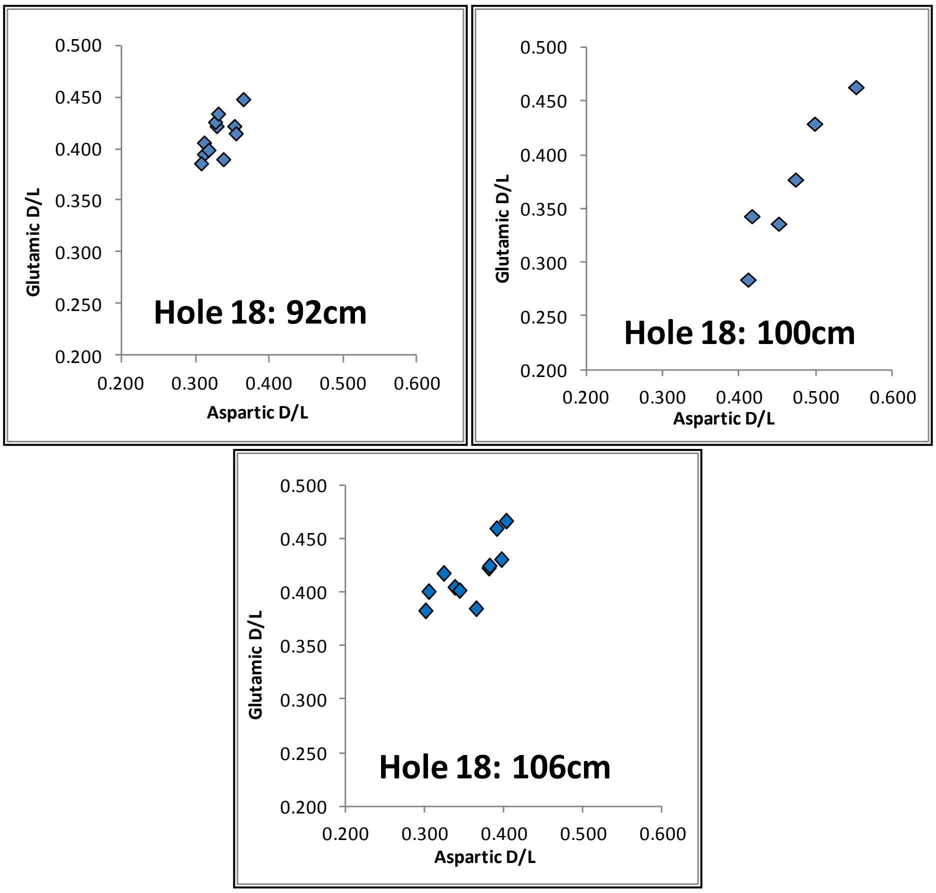

Figure 5.13: Comparison of the D/L ratio spread from horizons in hole 18 a) 92cm, b) 100cm and c) 106cm.

Age calibrations were based on the Holocene radiocarbon date obtained from the modern delta unit in hole 27 (Section 5.4) and the two Pleistocene TL ages obtained from holes 3 and 16 (Section 5.3). Based on the relative ages for those units the Glutamic acid D/L ratio produced a clear separation of Holocene and Pleistocene samples (Figure 5.14). However in aspartic acid the D/L ratio error margin (1σ) for the Holocene sample overlaps that of the Pleistocene samples (Figure 5.15).

The overlap of aspartic acid D/L in the Holocene and Pleistocene samples is likely to be because of the shallow burial depth of the Holocene sample (37cm) and the high temperatures experienced at Lake Frome (mean annual temperature ~20°C) which may have induced increased racemisation during the initial rapid stages of the aspartic racemisation curve (Figure 5.16). Increased aspartic acid racemisation at this initial stage causes D/L ratios in young fossils to be comparable to those of older samples who have passed the point where the curve begins to flatten, as is seen in Figure 5.16 at around 10 ka.

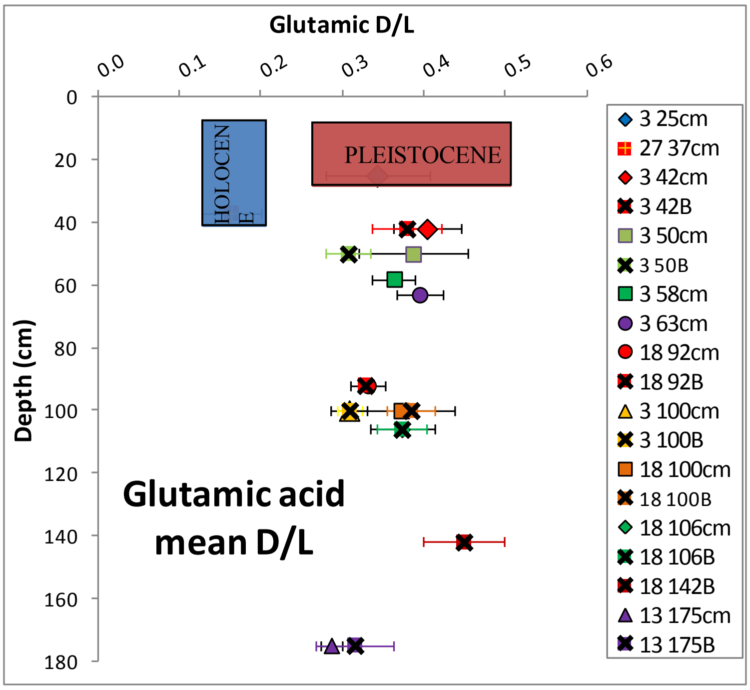

Figure 5.14: Rates of glutamic acid racemisation and separation of Holocene and Pleistocene D/L values for holes 27, 3 and 18. B denotes mean D/L of sample treated with NaOCl, represented as a cross on the graph. Black error bars are standard deviation produced from the standard procedure and coloured error bars from NaOCl treatment.

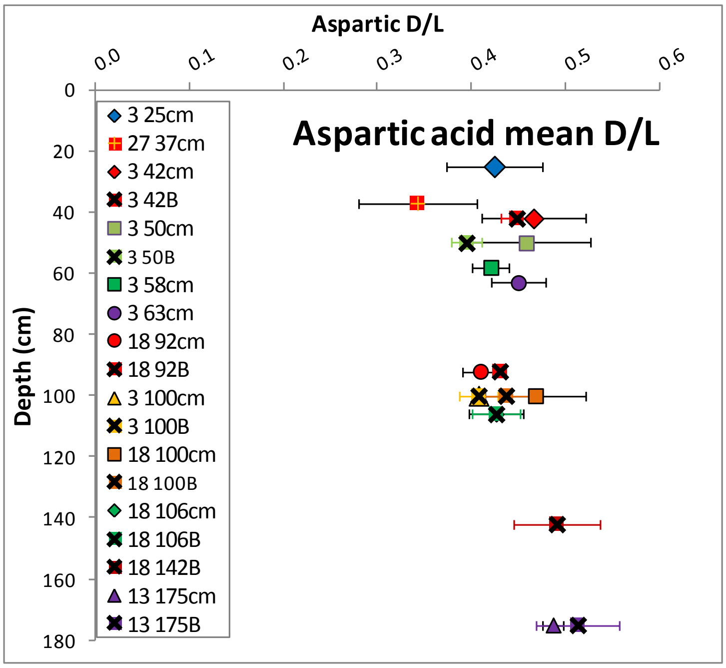

Figure 5.15: Rates of aspartic acid racemisation down core. Note the overlap within 1σ of Holocene sample from hole 27 with Pleistocene samples. B denotes mean D/L of sample treated with NaOCl, represented as a cross on the graph. Black error bars are standard deviation produced from the standard procedure and coloured error bars from NaOCl treatment.

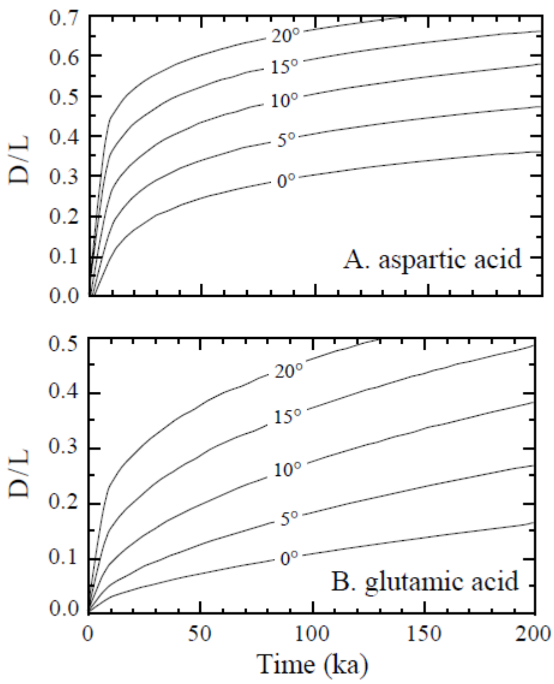

Figure 5.16: Modelled rates of racemisation showing the racemisation curve and the increased D/L values that can be caused by higher temperatures in A) aspartic acid and B) glutamic acid (after Kaufman 2003)

For the purposes of geochronology AAR ratios should show an increase with respect to depth provided that both mean annual and burial temperatures remain relatively stable and that fossils are preserved from leaching (Kaufman 2000; Reichert et al. 2011). However, down-core reversals in mean D/L values occurred in both aspartic and glutamic acid from the 50cm horizon down in hole 3 and this prompted a trial using NaOCl instead of H_2O_2. Amino acids are contained within both the inter-crystalline and the intra-crystalline calcitic composition in the ostracod valve (Bright & Kaufman 2011). Whilst the inter-crystalline component is subject to contamination and leaching the intra-crystalline portion is thought to be protected from those processes. The application of NaOCl is thought to have the effect of removing the contaminated and faster racemising inter-crystalline portion whilst leaving the uncontaminated, slower racemising intra-crystalline amino acids for AAR use (Bright & Kaufman 2011).

Pre-treatment with NaOCl did not resolve the reversal of D/L values from the lower horizons in hole 3 and the samples from the 100cm depth returned the same low values as the valves prepared using the standard procedure (Figure 5.17). The well preserved condition of the fragile valves means that reworking is unlikely to have occurred. Therefore the reversal pattern of racemisation with depth in hole 3 is likely to represent a slightly higher rate of racemisation in the ostracod valves in the upper horizons and slower racemisation of those at lower depths. It is also possible that the valves from the 100cm depth in hole 3 have been maintained in better preservation and have retained a larger proportion of the intra-crystalline proteins which racemise at a slower rate compared to the inter-crystalline fraction. Whatever the mechanism(s) affecting the D/L values in the ostracod valves from hole 3 it appears to be working across three different gradients with regard to burial depth (Figure 5.17).

Pre-treatment with NaOCl on ostracod valves from holes 18 and 13 was more successful and resulted in a geochronological trend of increasing aspartic acid D/L values with depth, which means that the D/L values could be used to obtain AAR ages (Figure 5.18).

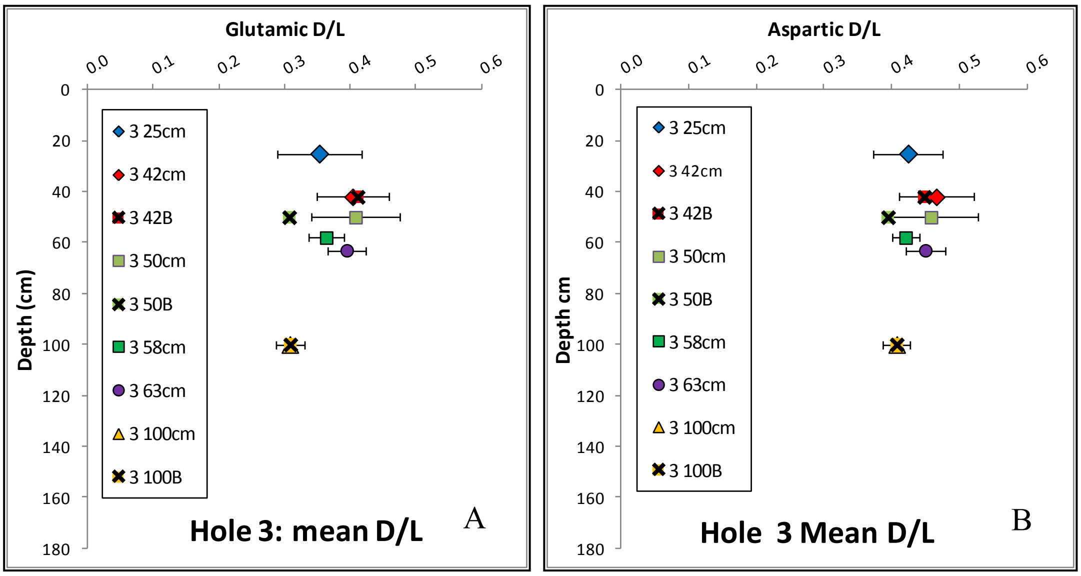

Figure 5.17: Reversals in the mean D/L values in ostracod valves with depth from Hole 3 (a) glutamic and (b) aspartic acid. B denotes mean D/L of sample treated with NaOCl, represented as a cross on the graph.

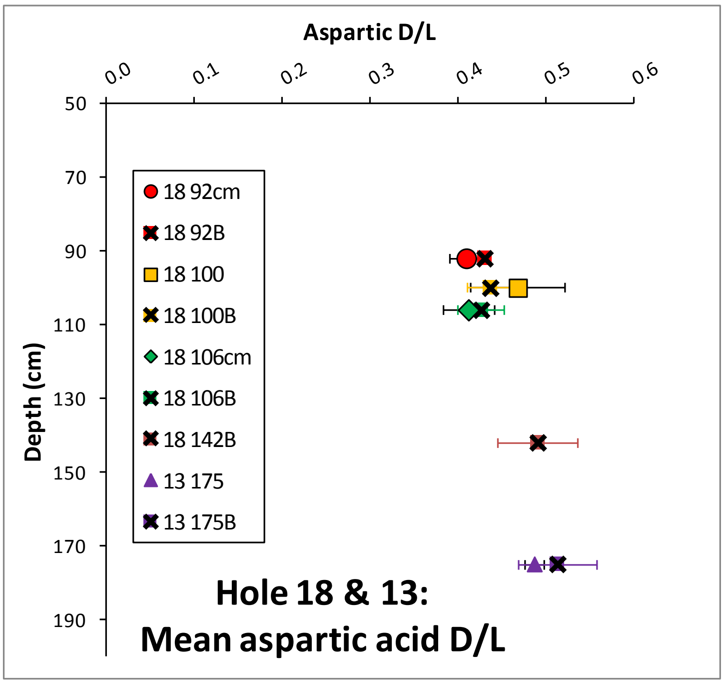

Figure 5.18: Trend of increasing aspartic D/L with depth. Note the depth horizon in hole 13 has been converted to depth below lake surface to be comparable to hole 18. B denotes mean D/L of sample treated with NaOCl, represented as a cross on the graph.

In their recent paper Bright and Kaufman (2011) deemed the pre-treatment of ostracod valves with NaOCl as unnecessary because it produced only slight differences in D/L values and it also wasn't effective in reducing neither error margins nor rejection percentages. AAR analysis carried out for this paper however found that the pre-treatment with NaOCl on the Lake Frome fossils did achieve some success as it produced geochronological corrections in two out of three cases when applied to apparent reversing trends. Treating the fossil valves from Lake Frome with NaOCl produced lower D/L values in the majority of the samples from above the burial depth of around 100cm but returned similar or higher values for the samples from below 100cm in both glutamic D/L (Figure 5.14) and in aspartic D/L values (Figure 5.15; Figure 5.18).

This result is likely to be because treatment with NaOCl removes the faster racemising intercrystalline proteins and younger contaminants and in doing so reduces the effect of the increased racemisation produced by the higher temperatures experienced at shallow burial depths (Bright & Kaufman 2011). Treatment with NaOCl on Lake Frome ostracod valves suggests that the application could be of some use in future procedures when attempting to reconcile D/L values of valves from shallow depths that would have experienced higher temperatures with those from lower down the core.

Aspartic racemisation rates in *Reticypris* sp. and *Diacypris* sp. valves from Lake Eyre were also added to those from Lake Frome (Figure 5.19). The aspartic acid D/L values graphed against depth shows conformity to the modelled amino acid racemisation curve from Kaufman (2003, Figure 5.14A) illustrating the possibility of future chronological application of ostracod valves from the Lake Eyre basin. TL ages of 106 $\pm$ 18 ka and 158 $\pm$ 24 ka were returned for horizons of 240cm and 350cm of Lake Eyre cores and fittingly the D/L rates for the Lake Eyre ostracods from depths of 175cm and 262cm were slightly higher than those from Lake Frome. Additionally the curve in Figure 5.19 appears to illustrate the occurrence of a species effect between *Diacypris* sp. and *Reticypris* sp. The mean racemisation rate of *Diacypris* sp. is higher in both horizons when compared to that of *Reticypris* sp. and is higher by more than 1σ than those of *Reticypris* sp. from the same horizon (262cm) at Lake Eyre.

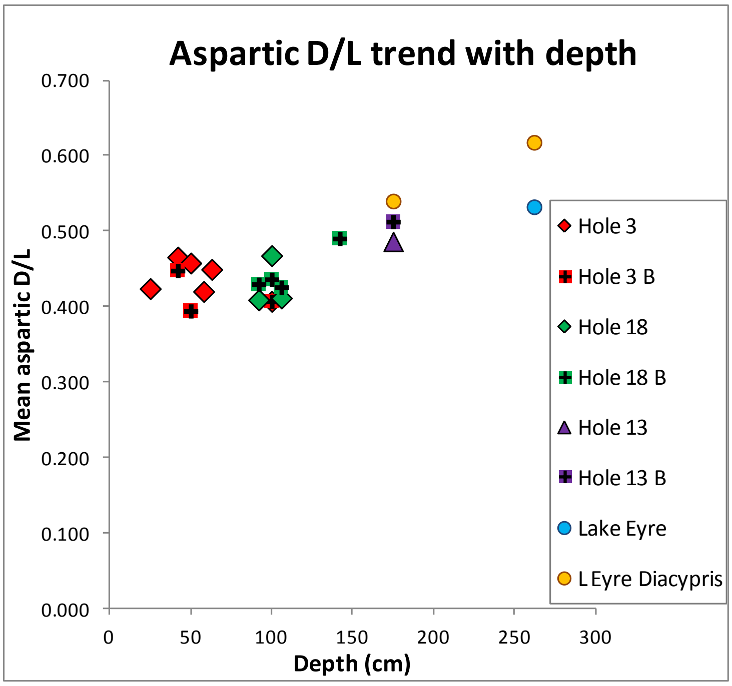

Figure 5.19: Racemisation curve of aspartic acid D/L rates from Lake Frome and Lake Eyre and comparison of *Reticypris* sp. and *Diacypris* sp. racemisation rates from Lake Eyre depth of 262cm. B denotes mean D/L of sample treated with NaOCl.

5.6.3 Numerical ages derived from AAR results

AAR was carried out on ostracod valves from sediment horizons that were dated or bounded by radiocarbon and TL ages to enable calibration of the AAR results and comparison between each of the holes and horizons. The 37cm depth horizon in Hole 27 was dated by radiocarbon to 2.8 $\pm$ 30 ka and horizons from holes 3 and 18 were bounded by two TL ages of 92 $\pm$ 6 ka and 81 $\pm$ 5 ka at depths of 135cm and 35cm respectively. As discussed above the aspartic D/L ratio obtained from hole 27 wasn't suitable to use for calibration because of the possibility that its linear function was tangential to the D/L progression in the other holes. It is acknowledged that the TL date is a measurement of the time since deposition and therefore doesn't describe the same event as do radiocarbon dating and AAR, but in this case the TL ages from Lake Frome proved to be highly consistent so they were used in absence of multiple radiocarbon ages to calibrate the AAR results.

The time zero aspartic D/L of 0.029 was averaged from the spread of aspartic D/L values (0.022 to 0.035) obtained by Bright and Kaufman (2011) from live collected ostracods. Calibrations were taken from the two TL ages obtained for holes 3 and 16 and aspartic D/L ratios were plotted against the square root of the TL ages in a linear regression model ($D/L/t^{1/2}$) as seen in Figure 5.20. This is carried out in order to obtain the slope of the line (Mc = 0.0015) then applied to the model of apparent parabolic racemisation kinetics as determined by Mitterer and Kriausakul (1989, Equation 1). $t= [(D/L)_s/Mc]^2$ Equation 1

Using the apparent parabolic method it was then possible to arrive at the AAR ages in Table 2. The aspartic D/L value (Hole 3 = 0.513), time zero value (0.029) and slope of the linear regression (Figure 5.20, y = 0.015) were entered in to Equation 1.

$t= [0.484/0.0015]^2$

t= 104,114

All errors were then propagated including the standard deviation of the mean aspartic value (0.045) ie. √(7)+(12)+(10.5)+(10)+(1.6)+(0.045) = 18%

18% (t= 104,114) = 19,076

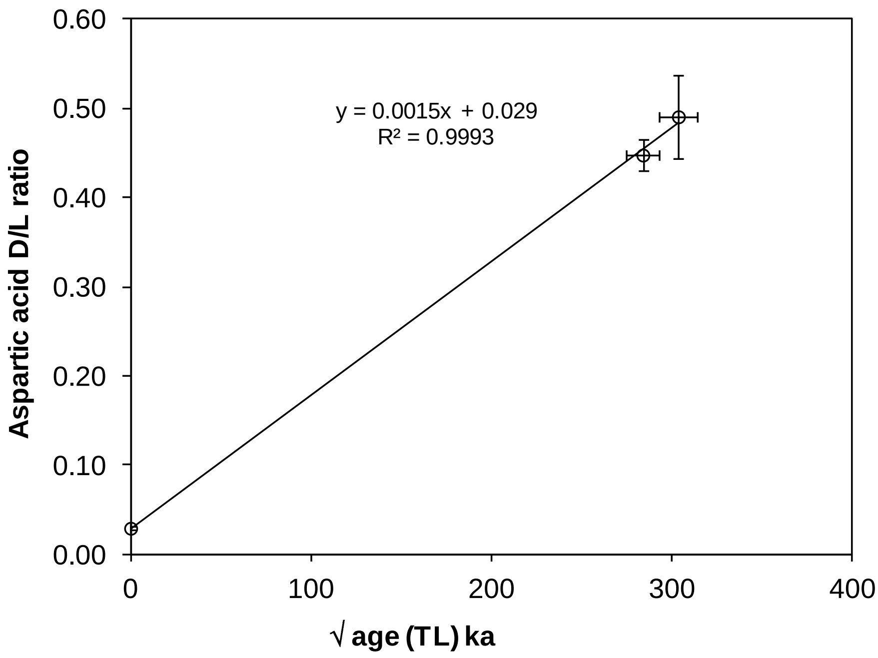

Figure 5.20: Linear regression of aspartic acid racemisation plotted against the two TL ages obtained from holes 3 and 16.

The error margin is high because an allowance of 10% was made for temperature variation in addition to the propagation of all other error margins. An AAR age of

112.9 ± 16.6 ka was also obtained for the *Reticypris* sample from Lake Eyre which is a good fit with the TL ages of 106 ± 18 and 158 ± 24 (Couri 2011) from 22cm below and 88cm above the sample respectively.

Table 2: AAR Ages

Hole	Depth	Asp D/L	Std Dev	AAR Age	Error
3	25cm	0.424	0.051	69,344	13,929
13B	175cm	0.513	0.045	104,114	19,076
LE2-6	262cm	0.533	0.041	112,896	20,131

5.7 Chapter Summary

The range of TL, AAR ages and the ^{14}C date obtained provide a clear late Quaternary and Holocene chronology to the stratigraphic units at the study site and the information from ostracod populations provides additional detail to what is already known about the sedimentary units of the embayment. These ages and palaeoenvironmental characteristics have allowed for clear and distinct phases within the basin to be identified from late Quaternary high lake and ecologically diverse period to fluctuating salinity and water levels and finally to that of the Holocene highly saline ephemeral environment. Because of the high temperatures and the arid climate of the study site problems were encountered in producing AAR ages, however the treatment of ostracod valves with NaOCl may prove a solution, only further study in this area will allow this to happen though.

Chapter 6: Synthesis of results

6.1 Introduction

This chapter provides a synthesis of the results obtained through analysis of the margins and lake floor sediments and the geomorphology of the study site. As illustrated in Figure 6.1 a series of units were identified within the embayment each representing separate and distinct depositional events. TL ages, an AMS radiocarbon date and AAR ages provide a geochronology for the study site and the information from microfossil assemblages was combined with that of the stratigraphy of the embayment to describe the evolution of the embayment through the late Quaternary. This information is then compared with the existing literature on Lake Frome and the Lake Eyre Basin to construct a multi-proxy account of climatic changes in the region throughout Quaternary.

6. 2 Evolution of the Lake Frome embayment through the Late Quaternary

Unit 1 Basal unit - Environment of deposition

The basal unit forms a part of the Eurinilla Formation (Callen 1976; Callen & Tedford 1976, see Figure 2.4) and indicates a lacustrine period of some permanency at Lake Frome with a wide lake body with the spread of lacustrine clays across the embayment, beneath both palaeodelta sites and beneath the current playa lake margins to the west (Figure 6.1). An AAR age of 104.1 $\pm$ 15.9 ka was obtained for this unit by using the TL ages as calibration points (see Section 5.3 and 5.5). The basal unit in the embayment is bounded by pebble gravel at the base marks high energy deposition at the onset of lacustrine conditions in the lake. In addition to this the presence of sand lenses and occasional pebble beds interbedded in the lacustrine clay indicates that the site was not too distant from a fluvial delta mouth and it also suggests that runoff was being produced by rainfall produced by effective precipitation in the south of Australia. This is because the only source of the larger pebble sized sediment along this western shoreline is the Flinders Ranges where the headwaters of the streams that drain to the lake rise 30km to the west of Lake Frome.

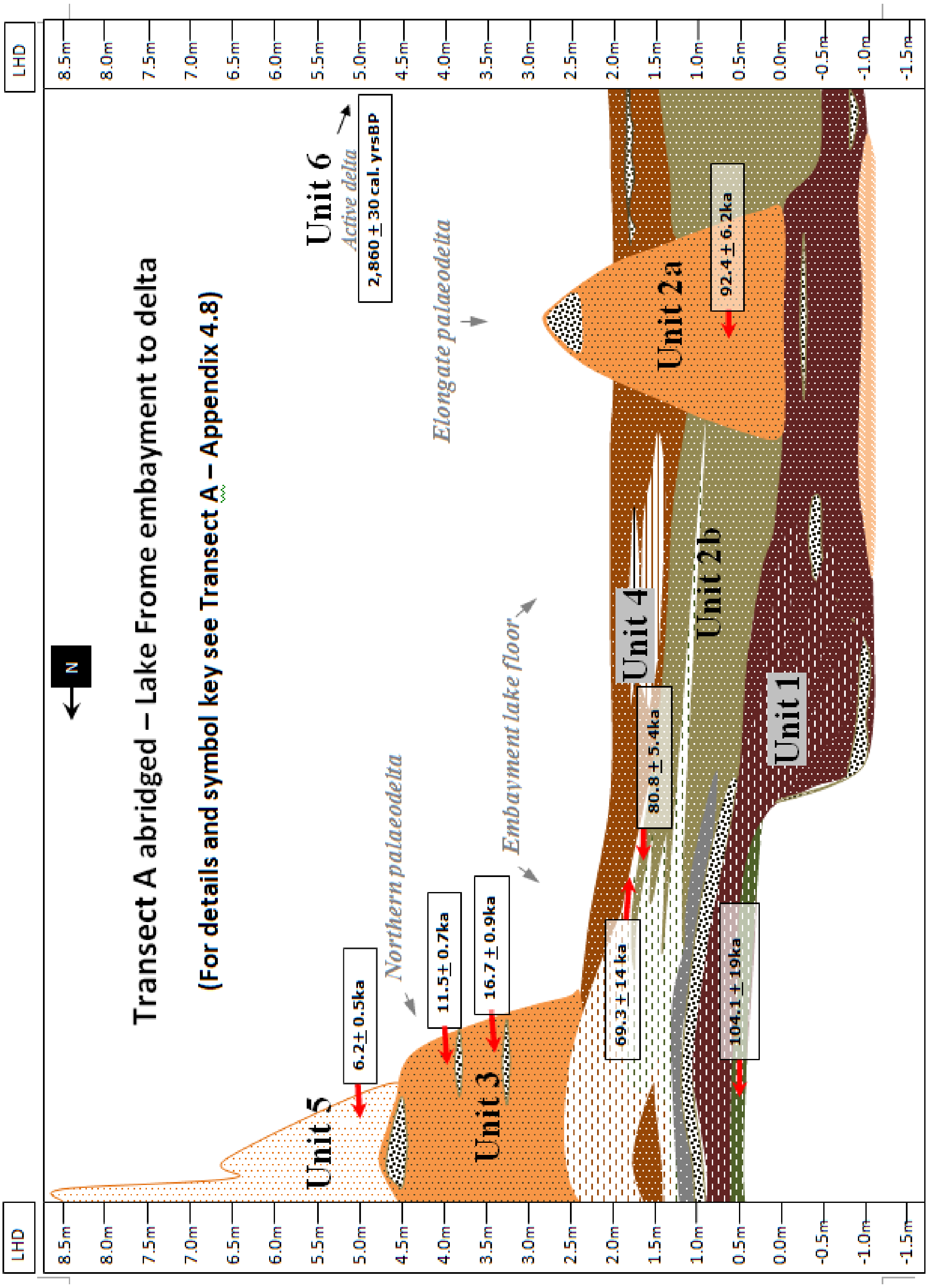

Figure 6.1: Units and ages from the embayment study site.

An abundance of small (~250mm) selinite crystals which forms under relatively stable lacustrine conditions (Magee 1991) were found in the oxidised upper part of this unit at hole 18 which indicates that lacustrine conditions were experienced for the duration of the deposition of this unit. The highly oxidised nature of the upper parts of the unit suggests that the lake bed was exposed to oxygenation prior to the deposition of the elongate palaeodelta and associated lake floor laminae. The microfossil content of the thick basal unit was found to display a more established and diverse fauna than in the following units and a death assemblage which indicates that major flooding events of fresh water runoff were occurred at the site, likely to be from influx from the Flinders Ranges deltas. If the water in the lake was already slightly saline, fresh water would not reach the site from Salt Creek in the north due to the large distances involved and opportunity for mixing and dissolution of salts along the way.

Unit 2a Elongate palaeodelta - Environment of deposition

TL ages of 92.4 $\pm$ 6.2 ka and 84.7 $\pm$ 5.6 ka were returned from samples taken at 0.67m (LHD) in hole 16 and at 0.86m (LHD) in hole 30 along the elongate palaeodelta. This unit also a part of the Eurinilla Formation (Callen 1976; Callen & Tedford 1976, see Figure 2.4) was deposited in the embayment as a subaqueous channel or levee of a fluvial delta and now appears as a raised and elongate landform extending across the playa lake floor (Figure 6.2). The current height of the elongate palaeodelta at just over 1m above the lake floor surface (see Figure 6.1) indicates that the delta built out into a lake with a water level of 2-4 m above the present surface at ~2m (LHD). However because the surface of the elongate palaeodelta has almost certainly been eroded the actual height of the lake during this stage cannot be accurately estimated.

The sands in hole 16 that contain rip-up clasts and overlying sands to an elevation of around 1m (LHD) in holes 16 and 30 are beds of massive medium-grained sands with floating granules. The massive sand units represent a higher sediment load discharging into the lake. Deposition of the massive units could indicate an increase in flood pulse volume and hence increased ability to move sediment but it could also be a consequence of deltaic progradation across the lake floor. Rapid deposition of sediments on entry to the low gradient, low energy conditions of the lake would explain the lack of bedding and massive structure of the units.

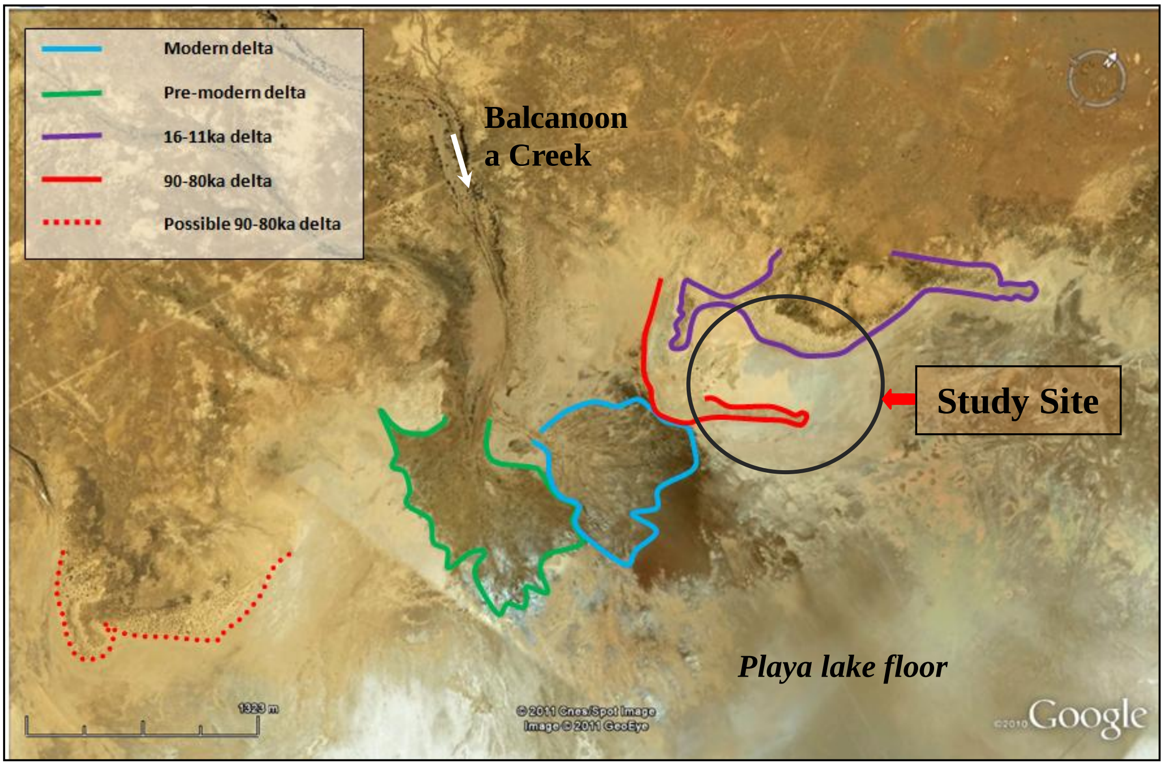

Figure 6.2: Location and chronology of deltaic deposits around the study site.
(Image from Google Earth 2011)

The general upward coarsening of the sediments culminating in the gravel bed at the tip of the landform are indicative of deltaic progradation into the lake. Additionally, the laminated nature of the beds and the existence of pebble beds suggest that delta building was achieved by a sequence of flooding events that varied in magnitude. The stabilising presence of the pebble bar is probably the reason for the preservation and current morphology of the tip of the elongate palaeodelta as the upper part of the deltaic sediments has almost certainly been eroded and reworked by subsequent lacustrine and aeolian episodes.

Subsequent aeolian reworking of the sediment on the elongate palaeodelta is evidenced by the close similarities found in Section 4.4 between the sediment from the massive near surface sands in hole 28 and the currently active dune sands along the western shore of the embayment. The location of the elongate palaeodelta adjacent to the dunes (Figure 6.3) and the grain size similarities between hole 28 sediment and the active dunes indicate that the sand from the elongate palaeodelta is the parent material of the dune sand which in turn indicates that the elongate palaeodelta was a landform with greater elevation than is evident today.

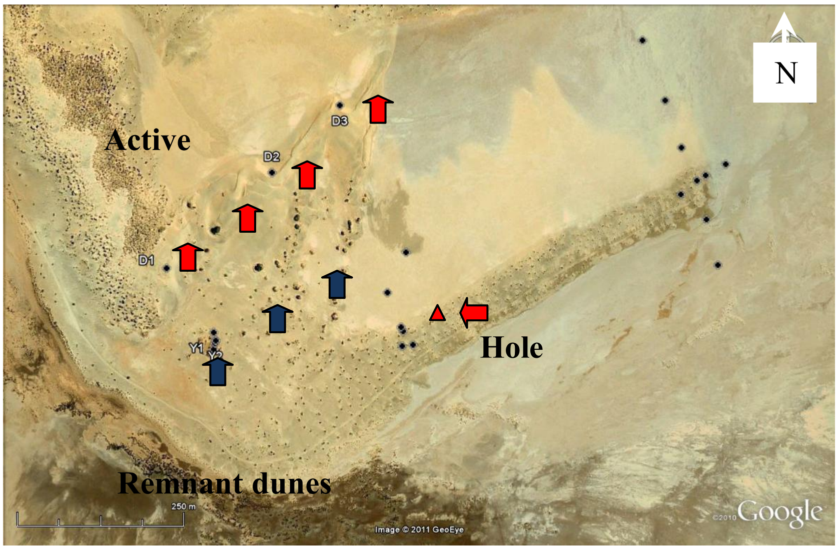

Figure 6.3: Location of hole 28 adjacent to active and remnant dune systems (Image from Google Earth 2011)

Unit 2b Laminated silt, clay and sand unit - Environment of deposition

A TL date of 80.8 ± 5.4 ka was obtained from a sand unit at an elevation of 1.7m (LHD) in hole 3 on the lake floor and an AAR age of 69.3 ± 14 ka was obtained from a series of thin silt laminae in the upper level silts at an elevation of 1.8m (LHD). These beds are thought to have been deposited in association with the sediments of the elongate palaeodelta as discussed previously in Section 4.3. Variations in the content of Illite/muscovite and microline minerals mainly reflect changes to the sand, silt and clay content and the depositional energy but no obvious change to the source of detrital sediments from that of the Flinders Ranges to the west. Gypsum in the form of selinite is found in this unit at holes 2 and 3 which indicates that relatively enduring lacustrine episodes were responsible for at least some of the deposition of the silt and clay laminae in this unit. The microfossil content of the laminated sand, silt and clay unit indicates a likelihood of large fluctuations in water salinity in the embayment. as was discussed in Section 5.5.

Unit 3 northern palaeodelta - Environment of deposition

The northern palaeodelta forms part of the Eurinilla Formation (Callen 1976; Callen & Tedford 1976, see Figure 2.4) and consists of a raised bench at the northern margin of the study site consisting of a two meter thick unit of fluvio-deltaic sands which were TL dated to 16.7 $\pm$ 0.9 ka and 11.5 $\pm$ 0.7 ka. Although the northern palaeodelta resembles a raised shoreline above the lake floor as discussed in Section 4.3.1, the lack of bedding and lack of beach detritus indicate that the unit is fluvio-deltaic in origin and the current shoreline is an erosional feature (Figure 6.1). The height of this unit at around 4.5 m (see Figure 6.1) above the playa lake floor indicates that the water column from 17 ka to 11 ka would have been at a minimum 4m above the present day lake floor height of 2m (LHD) The truncated nature of the northern palaeodelta could mean that the unit extended farther out across the embayment and that the associated lacustrine deposits are found farther into the lake.

Unit 4 oxidised lake floor sands - Environment of deposition

It is evident that the uppermost lake floor sediments have been quite extensively modified through the growth of displacive gypsum and halite precipitation, by ephemeral sheetwash evidenced by low tidelines of debris and by aeolian deposition of sand sized sediment. Because of the degree of alteration that has occurred within this unit it is almost impossible to gain an understanding of the environment under which it was deposited by analysis of the sediment itself but as previously mentioned it is likely that this sediment is highly modified delta fan sands. There are two silt lenses within the embayment that are possibly the lacustrine sediments associated with a Holocene lacustrine event (Figure 6.1). For the most part however, the lake floor sediments are today more a product of their subsequent alteration than their deposition. There is evidence of nearshore lacustrine carbonate accretion in holes 20, 21 and 22 but it seems that any other evidence of lacustrine deposition has been altered by the present playa lake conditions. The lake floor sands are made up of fine sands (150-250µm) which is most easily moved by aeolian transport through saltation (Mabbutt 1977) and it is likely that a portion of the sands within the oxidised lake floor sediments has been deposited in this way. It is often the case in the embayment that the fine sands at the very top of the lake floor sediments are slightly coarser than those below (as seen in holes 11, 1, 20, 22 and 32 see Appendix

4.3 for details) and often surface halite incorporates the fine sandy sediment evidentially because it has been blown onto the lake floor from the surrounding sandy landforms.

Unit 5 dunes - Environment of deposition

Two close TL ages of 6.9 ± 0.6 ka and 6.2 ± 0.5 ka were returned for the remnant dune situated along the western shoreline (near hole 25) and the dune atop the northern palaeodelta (hole 26) respectively. As discussed in Section 4.3.1 and above both of the dunes systems are likely to be source bordering, both are upwind of their source in a north-north-westerly direction. Whilst the dunes in the west have become partially indurate and a new dune sequence has formed to the north of the remnant forms the dunes along the northern palaeodelta remain as loose sand dunes, albeit partially stabilised by vegetation. The induration of the remnant dunes may be associated with their slightly older age and this may have occurred at the same time as the palaeosol was developing at the surface of the fluvio-deltaic sands in holes 12 and 13 across the northern palaeodelta. Following this sometime between 6.9 ka and 6.2 ka aridity may have increased again so that the dunes were reactivated in the west and those along the northern palaeodelta were initiated.

Unit 6 currently active delta - Environment of deposition

The currently active delta lies to the south of the study site and forms a subdued deltaic lobe which grades into the oxidised lake floor sediments across the playa floor (Figure 6.1). The sediment within the distal portion of the currently active delta at hole 27 consists of horizontal beds of highly oxidised silt and very fine sand. The highly oxidised nature of the silt and sand beds suggests that the deltaic flow has been ephemeral for the duration of the unit's deposition and that subaerial exposure has occurred between depositional episodes, as is occurring today. An organic rich horizon at around 0.37m depth (1.56m LHD) in hole 27 was dated by radiocarbon to 2,860 ± 30 cal. yrsBP which indicates that the present delta channel has been active since at least that time but the oxidised sediments extend down to at least 1.10m (LHD). The 2.8 ka date was obtained from charcoal or blackened woody remains within a layer of silt which could mark bushfires followed by a short period of renewed lacustrine deposition.

6. 3 Lake Frome embayment in context: comparison with literature

MIS 5 a-d (115 ka-75 ka)

Lacustrine conditions and high runoff are consistently reported in both the northern and southern Lake Eyre Basin during late MIS 5. Large meandering streams in the north-east channel country and the north-west of the basin fed into the basin from the north during 110 ka-100 ka. And speliothem records from the Naracoorte caves confirm that the periods of 115 ka–105 ka 100 ka–90 ka and 70 ka–85 ka were characterised by high effective precipitation in South Australia (Ayliffe *et al.* 1998).

The ages obtained from the study site for units 1 and 2 (a & b) add to a suite of similar ages reported by Nanson *et al*. (1992; 1998), Croke *et al.* (1996) and Cohen *et al*. (2011; 2011 in press) from their work on shoreline and fluvial sequences throughout the basin. The AAR age of 104 ka for the lacustrine unit at the study site correspond to the +13m (AHD) shoreline at Lake Eyre South reported by Nanson *et al.* (1992), the +15m (AHD) shorelines reported by Cohen *et al.* (2011) at lakes Frome and Callabonna and a near shore lacustrine deposit beneath a 65 ka beach ridge in the north of Lake Frome (Cohen *et al.* in press). Cohen *et al.* (2011; in press) provide a pooled mean of 96 $\pm$ 7 ka from shoreline sequences and argue that this lacustrine period saw lake levels of +15m and a body of water that extended from Lake Frome to Lake Eyre in the north. Whilst the evidence from the study site at Lake Frome provides additional correlation to this much cited lacustrine period in the basin it also provides insight into the relative reductions in lake depth, the permanency of the lake levels and the nature of the runoff flowing from the Flinders Ranges.

As illustrated in Figure 6.4, rather than one extended high water lacustrine period during Late MIS 5 the evidence from sediments and microfossils at the study site suggests flood pulses of varying magnitude, avulsion and migration of delta channels and albeit in relatively permanent lacustrine conditions, fluctuating lake and salinity levels. The stratigraphy of the Lake Frome study site indicates that in a period of high energy runoff a bed of pebbles and sand of unknown thickness was deposited at the base of unit 1 was followed by a lacustrine transgression which is likely to be associated with the +15m (AHD) Lake Mega-Frome level reported by Cohen et al. (2011). A +15m (AHD) shoreline would put the current lake floor at the Lake Frome study site under a water column of around 13m deep and would explain the deposition of thick silt and clay and the reducing condition of the lower beds of unit 1 (Figure 6.3). This was followed by a drop in water levels which is evidence by the oxidisation of the upper portion of unit 1, charaphyte growth and progradation of the elongate palaeodelta which built out at least 780m across the lake floor (see Figure 4.24). The current elevation of the elongate palaeodelta and TL ages suggest that the palaeodelta was prograding into a lake level of at least 4 m-6 m (LHD) between 92 ka and 81 ka. The stratigraphy and microfossil content of units 2a and 2b suggest fluctuating lake levels and sequences of flooding events that varied in magnitude but it also confirms the ongoing supply of runoff to the site from the Flinders Ranges at this time.

Whilst it appears that the period of lacustrine deposition at the Lake Frome embayment lasted for about 10 ka years longer than estimated by Cohen *et al.* (2011; in press see Figure 6.3 for ages). This discrepancy could be due to the fact that the ages by Cohen *et al.* (2011; in press) describe the high stand from palaeoshorelines only whilst evidence from the embayment describes a reduced lacustrine period. Nevertheless it seems that this period in the Lake Frome embayment actually resembles a combination of the mega Lake Frome from Cohen *et al.* (2011; in press) followed by a period that resembles stage IV as described by Magee et al. (2004) in the north of the Lake Eyre Basin.

MIS 4 (75 ka-60 ka)

It is possible that after a hiatus where a palaeosol developed in the upper units of the elongate palaeodelta similar to pedogenisis reported by Magee *et al*. (2004) in the Madigan Gulf prior to 70 ka, and that deltaic activity resumed again after this but ages are not yet available to confirm this. Reports of this period by Cohen *et al.* (2011) and Magee *et al*. (2004) describe a resumed lacustrine episode during MIS 4 but it seems that this period was also marked by aeolian activity. Nanson *et al.* (1998) and Fitzsimmons *et al.* (2007) both describe evidence of dune building around Lake Frome at this time. Cohen *et al.* (2011) describe evidence of a +15m (AHD) shoreline along the north-western shoreline of Lake Frome which yielded OSL Ages of 68 ka to 60 ka which correlate quite closely with the AAR age of 69.3 ± 14 ka from the thin lacustrine deposits in unit 2a at Lake Frome (Figure 6.3). No evidence of deltaic sediments were found at the study site to correlate to the MIS 4 date and speliothem growth was not optimal during that period (Ayliffe *et al.* 1998) so it is likely that the rivers supplying the western shoreline of Lake Frome were not highly active at the time. There is only sparse record of this lacustrine period at the study site as the silt unit from which the AAR date was recorded is a discontinuous unit and the microfossil content of the silt lenses within the lake floor sands had a low diversity indicating a short lived lacustrine episode.

MIS 3 (25 ka-60 ka)

Evidence from Cohen *et al.* (2011, in press) in the north of Lake Frome and from Lake Callabonna suggests that a lacustrine episode was also experienced during early MIS3 correlating to widespread reports of heightened runoff across the southern half of the continent at the time. It is interesting that none of the units at the study site returned ages for the MIS 3 period (50 ka-40 ka) in which speliothem records suggest that effective precipitation was high in South Australia, when Lake Mungo to the southeast was reportedly at a high lake phase and the rivers that drain southern NSW were actively accreting (Ayliffe *et al.* 1998; Page & Nanson 1996; Bowler *et al.* 2003). Cohen *et al.* (2011, in press) report +15 m (AHD) shorelines from around Lake Frome and Lake Callabonna at this time again which would mean that the study site would again be covered by a 13 m deep lake. There are a few possible explanations for the fact that very little evidence of this lacustrine episode is recorded at the study site such as a very short lived lacustrine episode where very little lacustrine sediments were deposited or that those sediments have been subsequent eroded or altered by desiccation.

MIS 2 (25 ka-20 ka)

No ages were returned for either fluvio-deltaic or dune building at the study site at the height of the LGM. But the flood pulses that built the elongate palaeodelta resemble the fluctuations of high and low magnitude floods which Haberlah *et al.* (2010) attributes to building the Brachina silts so it is possible that the rainfall pattern

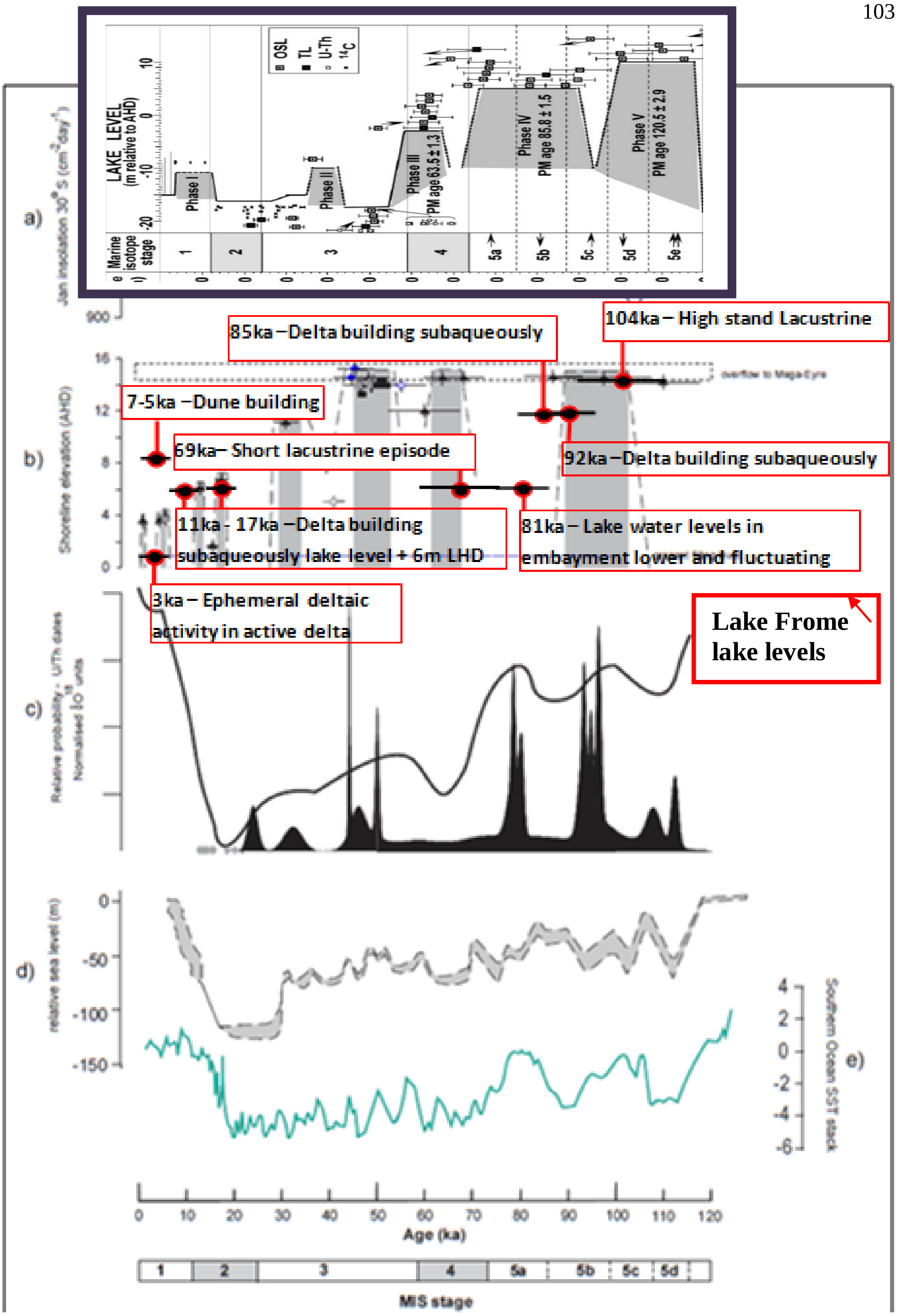

Figure 6.4: Comparison of the geochronology of units from Lake Frome (red circles and boxes) and b) Palaeoshoreline heights c) speliothem ages from Naracoorte Caves d) Relative sea level e) Sea surface temperature from the Southern Ocean. (Modified after Cohen *et al.* in press). Inset - Lake levels (modified after Magee *et al.* 2004).

in the Flinders Ranges wasn't unusual during the LGM but simply recorded in the ranges due to the heavy loess supply in rather than in the deltaic sediments. Resumed deltaic activity occurred at the study site as unit 3 the northern palaeodelta was deposited. Based on TL ages this was around 16.7 ka ± 0.9 ka to 11.5 ± 0.7 ka, but as the earliest date was recovered from an elevation of ~3.5m (LHD) it is suggested that deposition would have begun prior to 16.7 ka and could certainly have taken place towards the end of LGM height when temperatures were still around 9°C lower than the Holocene. It is reported from a wide variety of authors and proxies that lacustrine conditions were experienced at Lake Frome at around 17 ka. Both Draper and Jensen (1976) and Bowler *et al.* (1986) identified a lacustrine transgression from Lake Frome sediments at this time and both reported radiocarbon ages of around 20 ka to 16 ka from the lacustrine sediments. Similar ages were returned by Bowler *et al.* (1986) from the section of their core after what was recognised as the LGM disconformity. However there were several discrepancies with regard to the ages returned from the section prior to the disconformity which might refute their claim of LGM deflation.

Evidence from fossil pollens by Singh and Luly (1991) indicates that open woodlands surrounded the lake at this time and as their ages were sourced from Bowler *et al.* (1986) it is also possible that this occurred at the end of the LGM. Relatively higher numbers of winter rainfall dependant herb pollens and low fern spores also appear in the pollen record at this time indicating low temperatures, dry summers and wet winters support the theory that a northerly extension of Antarctic waters effectively pushed westerly frontal systems further into the continent at this time causing increased winter precipitation (Singh & Luly 1991; Barrows & Juggins 2005; Cohen *et al.* 2011). Cohen *et al.* (2011) report this lacustrine period as a Lake Mega-Frome at reduced levels from the previous high stands which would not see overflow to Lake Mega-Eyre in the north. The reduced lake level of 6.8m (AHD) reported by Cohen *et al.* (2011) however is synchronous with the deposition of the northern palaeodelta at the Lake Frome study site which also corroborates the height of the water column as indicated by the palaeoshoreline as the 16.7 TL date was from sediment taken from just below 3.5 m (LHD Figure 6.1).

As the TL ages from unit 3 at the study site cover the period of 16.7 ka to 11.5 ka and after as the top of the unit is eroded it is assumed that this whole period was one of deltaic progradation at the study site. Cohen *et al.* (in press) report an OSL date of 13.2 ± 0.8 ka from a 7m (AHD) shoreline at Salt Creek in which they cite possible evidence for a southward incursion of the monsoon as do Singh (1981) and Sing and Luly (1991) for lacustrine conditions that they report continue to or renew again at around 10 ka. Magee *et al*. (2004) also report lacustrine conditions at around 10 ka in the Madigan Gulf so it seems very likely that a strengthened monsoon was occurring in the north at least around 10 ka. This means that because the northern palaeodelta continued to prograded from 17 ka to 11 ka that both the winter and the summer rains were producing high volumes of water in the Flinders Ranges.

TL ages of 6.9 ± 0.6 and 6.2 ± 0.5 were obtained from dune sequences at the study site but these ages are not highly aligned with the literature. Most authors report renewed lacustrine conditions at Lake Frome between 6 ka and 5 ka. Singh (1981) and Singh and Luly (1991) report high grass and tree pollen counts at this time, and Bowler *et al.* (1986) and Cohen et al. (2011, In press) all report evidence of lacustrine conditions at that time in Lake Frome, Salt Creek and Lake Callabonna. Fitzsimmons *et al.* (2007) report a tentative high groundwater level and evidence of pedogenesis in the Strzelecki desert dunes at this time. Throughout the entire Holocene period however the evidence from Lake Frome describes a fluctuating environment of short lived lacustrine phases and aridity. Between 9 ka and 8 ka Bowler *et al.* (1986) and Singh (1981) report increasing aridity at Lake Frome which could have initiated dune building at the study site because of the high volume of sediment deposited by deltaic activity. Additionally the build up of sediment at the study site may have triggered channel avulsion moving the delta mouth and leaving no evidence of the renewed 5 ka lacustrine activity at the study site. The youngest TL date was also returned from the indurated remnant dune which indicates a hiatus of dune building activity and pedogenisis in the few hundred years between stabilisation of the remnant dune and activation of the dunes atop the northern palaeodelta.

MIS 1 (10 ka-present)

The final date obtained from the study site indicates that the delta mouth to the south of the embayment has been active since at least 2,860 ± 30 cal. yrsBP and that bushfires may have proceeded the short period of renewed lacustrine deposition. The AMS radiocarbon date of 2.8 ka is the age of the woody material within the sediment and as such only gives an indication of the maximum age of the sediment, this means that the unit could indeed younger. Whilst Bowler *et al.* (1986) and Cohen *et al.* (2011) report a short return to lacustrine conditions at Lake Frome and the southern Lake Eyre basin at around 5 ka and both Nanson *et al*. (1998) and Cohen et al. (2011, In press) report subsequent low level lacustrine episodes these ages are yet to be reported from the study site. Ephemeral deltaic flows have occurred subsequent to the dated horizon as 35cm of fine sand and silt lay above the dated section but it is also possible that these sediments have simply been reworked by sheet-wash and the lack of substantial datable material in the upper horizons haven't allowed for correlation between the upper units and the literature.

6. 4 Chapter summary

By examining the stratigraphy of both playa margins and lake floor sediments this study has been able to add greater detail to what is already known on climate change and the effects of climatic variation on the hydrology of the Lake Eyre Basin in the late Quaternary. Periods of lacustrine and fluvial activity have been identified at the Lake Frome study site that extend our knowledge of the site back to late MIS 5 and have provided evidence that sources of moisture from the Flinders Ranges were providing major input to the Lake Frome and Lake Mega-Frome lacustrine phases. In addition to this the identification of the deltaic units that form the current playa shorelines have also allowed estimation of minimum lake body heights which can be used to compare to palaeoshoreline evidence and will enable further investigation into both local and basin wide hydrological models.

Chapter 7: Conclusion and recommendations

7.1 Conclusion

Despite ongoing investigations into the climatic changes that have occurred throughout the late Quaternary, a number of contrasting theories exist with regard to the timing, duration and coverage of lacustrine and arid periods within the Lake Eyre Basin. Differences arise with regard to the timing and heights of the mega-lake periods that have occurred during the Quaternary and differences also arise with regard to the origin of the moisture source that has supplied the runoff for such periods. The major areas of contention with regard to climate variations in the Lake Eyre Basin include Nanson *et al.* (1998) and Cohen *et al*. (2011, in press) identifying a mid to late MIS 5 peak of the mega-lake system within the Lake Eyre Basin and Magee *et al.* (2004) arguing for a peak in early MIS 5 and another longer lower water stage in late MIS 5. Other areas of difference with regard to the reported climate record in the basin include coeval reports of LGM aridity and deflation at Lake Frome and heightened runoff in the Flinders Ranges which rise only 30 km to the west of the lake. Bowler (1976) and Callen (1983b) describe the formation of the islands of Lake Frome from deflation at the height of the LGM from 23 ka to 19 ka whilst Cock *et al.* (1999), Williams *et al*. (2001) and Haberlah *et al.* (2010) describe a 10 thousand year period of wetland or enhanced runoff and deposition of silt in the Flinders Ranges that continues through the LGM period.

A number of different palaeoenvironmental studies have been carried out on the lake floor sediments from Lake Frome. These reports have returned fairly consistent findings proving the validity of such studies despite the fact that they have been carried out on the same two sets of cores and several discrepancies which have been found in relation to the radiocarbon ages. These studies whilst valuable indicators of the lake environment also lack the ability to provide information on the depth of water in the lacustrine periods and the weather systems that might be responsible for runoff at the time. Due to increasing recognition that a superior picture of climatic related changes can be constructed with multi-proxy evidence from lake floor sediments and beach and deltaic formations a site was identified along the western shoreline of Lake Frome on which to base this study. The aims of this thesis involved interpreting and dating sections of the relational shoreline and lake floor features, examining the palaeoenvironmental characteristics of the site and assessing the usefulness of ostracods in the arid zone for AAR dating.

A series of transects were constructed from the data collected at the field site. The transects revealed a set of six different stratigraphic units deposited by separate and distinct environments within variations of a lacustrine and deltaic settings and a surface relief represented by the present day ephemeral conditions. Five TL ages were obtained during this study which ranged from 92 ka to 6 ka. The TL ages further enabled the distinction of the stratigraphic units and pointed a disjunction with regard to the separate features that defined the shorelines at the embayment. AAR was carried out on ostracods from the lake floor sediments. It was found that by treating the valves with NaOCl a geochronological trend could be established that enabled AAR ages to be derived using the apparent parabolic method. AAR ages were calculated for unit 1 in the embayment which came to 104 ka and for unit 2a in the upper embayment floor which came to 69 ka. An AMS radiocarbon date was also obtained for the active delta to the south of the embayment which determined accretion had been occurring in the present day location since at least 2.8 ka.

Analysis of grain size parameters was carried out on the sediments from both unit 2a the elongate palaeodelta and unit 3 the northern palaeodelta in order to establish the mode of their deposition. Morphologically the elongate palaeodelta resembles a shore attached spit complete with a sandy surface and what might be a wave built relief at around 1m above the playa lake floor. The northern palaeodelta resembles a shoreline that has possibly been cliffed or truncated by lacustrine periods. However the sediments of both units revealed none of the characteristic content or bedding that would be expected for wave built features. Using a combination of techniques from Friedman (1961) and Sun *et al.* (2002) an attempt was made to confirm the mode of their deposition by grain size parameters. By a process of elimination it was found that both sets of sediments were likely to be fluvial sediments that had been deposited in a deltaic setting and whose upper sediment had been subsequently modified by aeolian processes to a degree that reflected the different ages of the units. In the case of the upper sediments of the elongate palaeodelta it was also found that they were highly likely to be source material for the dunes that were currently active 250m north of the landform across the western margin of the embayment.

The results from geochronology, stratigraphy and palaeoenvironmental analysis of the Lake Frome study site were compiled and compared with the existing literature on climatically driven environmental change in the Lake Eyre Basin. It was found that where there was evidence of lacustrine and deltaic events at Lake Frome, they had high correlation with the reported mega-Frome episodes by Cohen *et al*. (2011, in press). The period during MIS 5 in the Lake Frome embayment was found to demonstrate evidence of the +15 m (AHD) shoreline reported by Cohen *et al.* (2011; in press) and also to partly correlate to Magee *et al.* (2004) stage IV in the north of the Lake Eyre Basin because of the spread of ages and the reduced lake levels that continued to 81 ka in the embayment. The evidence from the study site at Lake Frome also proves that the Flinders Ranges were suppling ongoing runoff to the site from weather systems that bring precipitation to southern Australia for the duration of this period. Following this evidence from the study site at Lake Frome provides an AAR age of 69 ka from the upper portion of unit 2b. Limited representation of this unit at Lake Frome is thought to signify a short lived lacustrine period for which there were neither associated deltaic sediments nor evidence from other sources to indicate runoff in the Flinders Ranges. And no dated evidence has been found in the embayment yet of the reported MIS 3 lacustrine period reported by Cohen *et al.* (2011; in press) which would have seen a +13 m (AHD) lake at the site.

TL ages indicate heightened winter precipitation in the south of Australia and in the Flinders Ranges just around the end of height the LGM as the TL age of 17 ka was returned from the mid and upper portions of unit 3 the northern palaeodelta. Similar ages were returned by Bowler *et al.* (1986) from the section of their core after what was recognised as the LGM disconformity. However there were several discrepancies with regard to the ages returned from the section prior to the disconformity which might refute their claim that a disconformity in the core marked widespread LGM deflation in the Lake Frome Basin. Cohen *et al.* (2011) report this lacustrine period as a Lake Mega-Frome but with reduced levels from the previous high stands and without connection to Lake Mega-Eyre in the north. The reduced lake level of 6.8m (AHD) reported by Cohen *et al.* (2011) is reflected by the height of the lower TL dated sediment, which at just below 3.5 m (LHD) would have built into a lake level of around 5-6 m (LHD). Evidence of a summer monsoonal incursion from the north that followed the end of the LGM at around 13 ka and 10 ka saw a continued progradation of the northern palaeodelta at the study site which indicates that both the winter and the summer rainfall volume at the time were high. Following this the sedimentary record at Lake Frome from the beginning of the Holocene suggests that ephemeral conditions prevailed which is also generally reflected by all studies of the region.

The geochronology and stratigraphy from the study site at Lake Frome provide consistent and coeval ages with a good deal of the literature. However large gaps in shoreline sedimentation were evidenced by the differences in TL ages returned for the deltaic features that form the playa shoreline at the study site (see Figure 6.2). This finding demonstrates the real need for a multi-proxy approach to environmental reconstruction when using Australian arid zone lakes to investigate climate variation within the Quaternary. The vast accommodation space of the playa lakes and their tributaries in the Lake Eyre Basin mean that studies that rely too heavily on one proxy or similarly studies that rely too heavily on one study site as a indication of environmental change can only provide a one-dimensional or site specific representation of environmental factors at best. This thesis demonstrates that the mechanisms driving climate change, the response of Australian arid zone lakes and the perturbations experienced within the climate during the Quaternary have not left a uniform signature in the sedimentary record across the Lake Eyre Basin. A multi-proxy approach where lake floor sediments, shoreline, deltaic and aeolian features are studied and compared with evidence from other sites is the only way to unearth the real picture of environmental and climate change. Studies that rely solely on single proxy studies or single environments within lake studies take a real chance that vital evidence will be missed because it is simply not represented in the sedimentary record in that one instance.

This study has demonstrated that by using a multi-proxy approach to palaeoenvironmental interpretation new evidence can be found that adds to our understanding of the timing, effects and synchronicity of the wet and arid periods which were experienced in the Lake Eyre Basin during the late Quaternary. A major lacustrine period was identified in late MIS 5 at around 104 ka with shorelines that extended a distance further to the west than the present day play shore. Runoff from the Flinders Ranges was found to be consistently supplying high volume runoff to Lake Frome throughout an extended period of late MIS 5 between 92 ka and 81 ka and for an extended period in MIS 2 just subsequent to the height of the LGM, before 17 ka and up until11 ka. Palaeodelta heights were found to indicate lake water heights of around 4-6m (AHD) during the times of delta progradation. Finally evidence that aeolian activity was the primary source for the redistribution of sediment at the study site from around 7 ka to 6 ka indicates that conditions similar to what exists today at the site were in operation from that time.

7.2 Recommendations

The work carried out on this thesis has revealed that the study of adjacent shoreline, deltaic and lake floor facies can provide detail to what we already know about late Quaternary climates across the Australian continent. To add further to this additional analysis of the shoreline structures along the western periphery of Lake Frome would enable quantification of the role that runoff from the Flinders Ranges has played in past lake filling and mega-lake filling events. Investigation into the other spit-like structures that litter the western shoreline of Lake Frome would also confirm the role that runoff from the Flinders Ranges has had in contributing to lake filling events. This could also lead into hydrological modelling which could determine if the volumes of runoff that were received from the Flinders Ranges could fill a basin the size of Lake Frome and lead to overflow to the other lake of the Lake Eyre Basin. Finally the work carried out in AAR for this thesis only touched on the work that needs to be done to understand the mechanisms and also the benefits to using ostracods to produce chronologies for playa environment. Heating experiments and further work is required to understand how and if NaOCl can be used to produce robust geochronological results from arid zone ostracods.

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APPENDIX 4.1: PERMIT TO UNDERTAKE SCIENTIFIC RESEARCH

Government of South Australia
Department of Environment and Natural Resources

PERMIT TO UNDERTAKE SCIENTIFIC RESEARCH

Permit Holder:
Miss AC Barrett
University of Wollongong
School of Earth & Environmental Sciences
Northfields Avenue
GWYNNEVILLE
2522

Project Title: Evidence of Holocene climatic change from Lake Frome beach and lacustrine deposits.

Permit Number: Y25926-1

This permit is valid from 1/04/2011 to 30/06/2011 unless cancelled or revoked

for

Paul Caica
Minister for Environment and Conservation

YOU MUST CONTACT THE APPROPRIATE REGIONAL OFFICE BEFORE COLLECTING ANY SPECIMENS OF FLORA OR FAUNA OR ENTERING A RESERVE

FAILURE TO DO THIS MAY RESULT IN PERMIT WITHDRAWAL AND A FINE

CARRY THIS PERMIT WITH YOU WHEN CONDUCTING RESEARCH IN THE FIELD
A photocopy plus other ID must be carried by any additional named collectors who are collecting independently

For any enquiries relating to this permit, contact:
Department of Environment and Natural Resources
Postal Address: GPO Box 1047, Adelaide, 5001, SA
Location: Plant Biodiversity Centre, Hackney Road, Adelaide
Telephone 08 8222 9435 Fax 08 8212 4661
Email: DENRresearchpermits@sa.gov.au

Y25926-1 1

APPENDIX 4.2: AARD PERMIT

Government of South Australia
Department of the Premier and Cabinet

Physical Id. DPC11D01574
File No. DPC11/0123

GPO Box 2343
Adelaide SA 5001
DX 56201
Tel 08 8226 3500
Fax 08 8226 3535
www.premcab.sa.gov.au

Ali Barrett
Honours Student
University of Wollongong

Dear Ali

Thank you for your correspondence (email) dated 28 February 2011, regarding your research on the geomorphology, sedimentology and hydrology of Lake Frome. The field work is to be conducted in the Lake Frome regional reserve and the Vulkathana-Gammon National Park boundary as per coordinates provided by you.

I advise that the Central Archive, which includes the Register of Aboriginal Sites and Objects (the Register), administered by the Department of the Premier and Cabinet-Aboriginal Affairs and Reconciliation Division (DPC-AARD), has no entries for Aboriginal sites within the project location.

The Register is not a comprehensive record of all Aboriginal sites and objects in South Australia. You are advised that sites or objects may exist in the proposed development area, even though the Register does not identify them. All Aboriginal sites and objects are protected under the *Aboriginal Heritage Act 1988* (the Act), whether they are listed in the Register or not. Land within 200 metres of a watercourse (particularly the River Murray and its overflow areas) in particular, may contain Aboriginal sites and objects.

It is an offence to damage, disturb or interfere with any Aboriginal site or damage any Aboriginal object (registered or not) without the authority of the Minister for Aboriginal Affairs and Reconciliation (the Minister). If the planned activity is likely to damage, disturb or interfere with a site or object, authorisation of the activity must be first obtained from the Minister under Section 23 of the Act. Section 20 of the Act requires that any Aboriginal sites, objects or remains, discovered on the land, need to be reported to the Minister. Penalties apply for failure to comply with the Act.

It should be noted that this correspondence only addresses Aboriginal heritage matters in the context of the *Aboriginal Heritage Act 1988* and does relate to any native title considerations that may, or may not, be relevant to the land area over which you have requested information.

For further information, please contact the Aboriginal Heritage Branch on telephone (08) 8226 8900.

Yours sincerely

Justin Wearne
SENIOR HERITAGE INFORMATION OFFICER
ABORIGINAL AFFAIRS & RECONCILIATION DIVISION

08 March 2011

APPENDIX 4.3: GRAIN SIZE DATA AND CONTENT

Layers cm	Sample depth cm	LHD	Munsell colour	Average grain size	% Sand	% Silt	% Clay	Granules	Pebbles	Cobbles	Palaeosol	Gypsum
	Hole 12											
	0	901.2	5YR 5/6	250.864	98.54	1.01	0.45					
	100	801.2	5YR 5/6	204.369	97.41	1.62	0.97					
	200	701.2	5YR 5/6	215.178	95.53	2.91	1.56					
	300	601.2	5YR 5/6	191.172	90.90	6.50	2.60					
	400	501.2	5YR 5/6	211.825	89.95	7.56	2.49					
450-540	450	451.2	5YR 6/6	213.359	95.04	3.26	1.71					
540-585	500	401.2	5YR 5/6	209.707	76.69	17.30	6.02					
540-585	520	381.2	5YR 4/6	129.585	53.27	30.98	15.75				X	
540-585	550	351.2	2.5YR 4/4	95.264	46.63	30.34	23.02					
585-615	600	301.2	5YR 5/6	240.541	89.98	6.78	3.24					
585-615	615	286.2	5YR 4/6	258.182	66.72	18.60	14.67	X				
630	630	271.2	5YR 5/6	305.851	86.47	8.70	4.84					
	Hole 13											
0-145	100	544.6	5YR 5/6	215.456	89.82	6.99	3.19					
0-145	145	499.6	5YR 5/6	208.856	82.48	10.24	7.28	X	X			
145-180									X			
180-250	200	444.6	5YR 6/6	258.285	87.81	8.22	3.97				X	
180-250	250	394.6	5YR 4/6	211.807	65.54	18.87	15.59				X	
250-290	300	344.6	5YR 4/6	233.657	71.70	17.23	11.07					
290-365	325	319.6	5YR 4/4	340.648	85.85	9.96	4.19					
290-365	360	284.6	5YR 4/4	386.698	79.90	15.50	4.60	X				
365-400	365	279.6	5YR 4/6	71.116	39.21	30.39	30.40					
365-400	365-375	370	5YR 4/6	69.486	33.36	45.95	20.69					
400-470	400	244.6	5YR 4/6	101.538	44.72	36.26	19.01					
	475	169.6	7.5YR 4/6	176.904	77.84	14.69	7.47					
500-520	500	144.6	Gley 6/5GY	94.48	41.14	38.87	20.00					
520-535	520	124.6	2.5Y 6/3	110.533	57.87	30.84	11.29					
535-560	535	109.6	2.5Y 6/4	124.747	67.64	24.03	8.33					
562	562	82.6	2.5Y 6/3	135.717	60.46	27.30	12.25		X			
570-585	570	74.6	5YR 4/4	21.591	4.71	65.26	30.02					
585-590	585	59.6	5YR 4/6	111.123	13.31	52.30	34.38					
590-600	600	44.6	10YR 6/2	62.911	16.73	45.13	38.14					
	Remnant Dune											
	TL dated	370.1	5YR 4/6	163.52	83.18	10.46	6.35					
34-40	36	334	7.5R 5/6	145.838	57.5	19.38	23.12				X	
40-56	56	314	5YR 4/6	426.05	72.37	17.75	9.88					
	Hole 26											
	26	584.5	5YR 5/6	216.398	90.7	6.03	3.26	X	X			
	Hole 25											
10-30	20	350.1	5YR 4/6	181.057	73.23	17.5	9.27					
33.5-40	40	330.1	5YR 5/6	252.493	70.97	16.56	12.47	X	X			

Layers cm	Sample depth cm	LHD	Munsell colour	Average grain size	% Sand	% Silt	% Clay	Granules	Pebbles	Cobbles	Palaeosol	Gypsum
	Hole 14											
30	30	419.2	5YR 6/4	176.955	71.81	23.28	4.91	X				
	60	389.2	5YR 5/6	217.461	64.22	21.38	14.39		X			
	100	349.2	5YR 4/6	340.96	87.85	8.36	3.80					
	115	334.2	7.5 YR 4/6	390.939	86.90	8.91	4.19					
130-150	130	319.2	7.5 YR 4/6	395.082	88.22	8.71	3.07					
160-165												
165	165	284.2	5YR 4/6	51.861	30.49	41.16	28.36					X
165-200	200	249.2	5YR 4/6	58.215	32.54	46.70	20.76					
260	260	189.2	2.5Y 5/4	119.309	44.23	36.55	19.22					
260-300	270	179.2	5Y 6/2	56.957	12.58	54.67	32.75					
300-315	300	149.2	5Y 6/2	33.748	19.38	54.71	25.91					
315		449.2										
325	325	124.2	5Y 6/2	147.89	63.11	26.79	10.10	X	X			
	Hole 11											
0												
0-10	5	235.7	7.5 YR 5/6	197.021	77.81	15.75	6.44					
10-12	11	229.7	7.5 YR 5/6	178.379	67.84	21.38	10.77		X			
12-30	20	220.7	7.5 YR 4/6	198.36	45.23	41.51	13.26					X
30-35	33	207.7	5YR 4/6	50.996	23.31	53.14	23.55					
35-39	37	203.7	5YR 4/6	85.253	36.22	40.89	22.88					
39-46	45	195.7	2.5Y 6/2	33.437	10.70	57.70	31.59					
46-50	49	191.7	2.5Y 5/4	91.487	43.15	37.18	19.67					
50-60	55	185.7	2.5Y 6/3	105.438	42.59	37.60	19.81					
75-85	75	165.7	Gley 7/5GY	92.178	25.14	41.72	33.14					
85-95	85	155.7	2.5Y 6/4	104.241	53.72	31.32	14.95					
90-95	95 upper	145.7	2.5Y 5/3	71.297	41.79	43.43	14.77					
90-95	95 lower	145.7	2.5Y 6/2	92.541	46.26	36.42	17.32					
107-123	107	133.7	2.5Y 5/2	59.136	43.22	49.24	7.54					
123-130	123	117.7	2.5Y 5/2	130.299	70.73	22.99	6.28					
130	130	110.7	2.5Y 6/2	175.216	76.55	16.48	6.97	X	X			
	Hole 3											
0-3	2	202.7	5YR 4/4	191.979	65.88	21.45	12.67	X				X
16-17	16	188.7	5Y 6/2	52.544	22.22	49.63	28.15					X
17-20	19	185.7	2.5Y 6/3	39.095	14.40	54.16	31.44					
20-31	25	179.7	5Y 6/2	54.846	18.19	53.12	28.68					
31-33	32	172.7	5Y 6/2	176.521	73.40	19.67	6.93					
	34.5	170.2		93.724	41.75	35.92	22.32					
33-36	35	169.7	5Y 6/1	82.927	47.82	39.74	12.44					
36-38	37	167.7	5Y 6/3	46.448	16.74	48.70	34.55					
38-41	39	165.7	2.5Y 6/4	125.246	51.12	29.77	19.11					
41-44	42	162.7	Gley 6/10Y	43.521	28.77	43.37	27.86					
44-46	45	159.7	10YR 5/3	108.059	60.41	27.61	11.99					

Layers cm	Sample depth cm	LHD	Munsell colour	Average grain size	% Sand	% Silt	% Clay	Granules	Pebbles	Cobbles	Palaeosol	Gypsum
46-54	50	154.7	2.5Y 5/4	110.487	51.25	33.15	15.59					
54-57	56	148.7	5Y 6/2	65.201	32.26	44.03	23.70					
57-60	58	146.7	2.5Y 6/3	146.402	62.55	26.88	10.57					
60-65	63	141.7	5Y 6/2	81.329	40.74	41.38	17.89					
65-77	68	136.7	2.5Y 5/3	76.849	60.08	31.39	8.52					
87-100	87	117.7	2.5Y 6/2	106.274	68.27	24.74	6.99					
100-105	100	104.7	10YR 5/2	119.234	64.52	27.67	7.81					
105	105	99.7	10YR 5/2	151.419	72.64	18.54	8.82		X			
	Hole 1											
0-10	5	203.9	7.5 YR 4/6	169.746	81.38	13.18	5.45					
10-20	15	193.9	7.5 YR 4/6	161.703	80.85	13.29	5.86					
20-25	22.5	186.4	7.5 YR 4/6	197.44	69.76	20.52	9.71					X
25-33	28	180.9	5YR 4/4	149.082	76.67	14.10	9.24					
37-42	40	168.9	5Y 6/2	50.427	23.15	49.16	27.69					X
42-65	43	165.9	5Y 6/2	105.189	44.59	38.06	17.35					
42-65	53	155.9	2.5Y 5/3	135.092	72.00	22.06	5.95					
42-65	56	152.9	2.5Y 6/2	84.432	46.22	40.00	13.78					
65-80	81	127.9	2.5Y 5/3	67.057	41.74	45.52	12.74					
92-100	96	112.9	2.5Y 5/2	137.018	77.48	17.05	5.47					
100-110	106	102.9	2.5Y 5/2	108.971	55.41	30.48	14.12					
	131	77.9	10YR 5/2	142.471	79.95	15.04	5.02					
	Hole 15											
60-84	60	147.5	10YR 5/3	113.655	51.12	33.71	15.17					
84-95	84	123.5	2.5Y 5/3	59.559	40.47	46.95	12.58					
95-107	95	112.5	2.5Y 5/3	95.692	60.62	30.87	8.51					
107-120	107	100.5	2.5Y 5/3	105.626	58.54	29.94	11.53	X				
138-143	138	69.5	10YR 5/3	132.701	78.20	14.10	7.71					
165-175	165	42.5	5YR 4/4	60.357	21.00	37.83	41.17					
200	200	7.5	7.5 YR 4/6	83.312	51.19	30.29	18.52	X				
211-228	211	-3.5	7.5 YR 4/6	177.46	62.30	23.14	14.56	X				
240-248	240	-32.5	5YR 4/6	52.038	29.35	30.20	40.45					
265-270	265	-57.5	5YR 4/6	36.392	50.95	33.83	15.22					
290	290	-82.5	7.5 YR 5/4	114.256				X	X			
	Hole 2											
	17	185.7	7.5 YR 4/4	131.063	70.76	21.09	8.15					
21-26	24	178.7	10YR 3/4	59.403	30.42	48.44	21.14					
	36	166.7	5YR 4/4	64.769	36.54	46.36	17.10					
	60	142.7	5YR 4/4	60.582	36.27	45.23	18.50					
	72	130.7	7.5YR 4/4	39.449	19.44	53.93	26.63					
	76	126.7	7.5YR 4/4	103.098	51.01	35.39	13.60					X
90	90	112.7	7.5YR 4/4	133.031	69.10	22.81	8.09					
	94	108.7	10YR 5/2	99.172	60.97	31.56	7.48					
	97	105.7	2.5Y 5/2	17.678	1.88	69.15	28.97					X

Layers cm	Sample depth cm	LHD	Munsell colour	Average grain size	% Sand	% Silt	% Clay	Granules	Pebbles	Cobbles	Palaeosol	Gypsum
	110	92.7	7.5 YR 5/3	165.136	73.71	17.05	9.24					
	110	92.7	7.5 YR 5/3	165.136	73.71	17.05	9.24					
120-133	120	82.7	7.5 YR 5/3	135.227	75.64	17.73	6.63					
120-133	133	69.7	7.5 YR 5/3	150.874	76.33	18.23	5.44					
144 and up	144	58.7	7.5 YR 4/4	197.34	70.69	19.07	10.24	X				X
160-170	160	42.7	5YR 4/4	8.855	0.85	54.42	44.73					
170-175	171	31.7	7.5YR 4/6	59.252	21.22	42.08	36.70					X
180-190	185	17.7	7.5YR 4/6	214.631	62.31	22.30	15.39					
190-210	200	2.7	7.5YR 4/6	188.287	53.01	27.77	19.21					X
190-210	210	-7.3	7.5YR 4/6	90.373	33.28	29.35	37.37					
210-235	220	-17.3	7.5YR 4/6	89.019	37.51	28.48	34.01					
235-260	235	-32.3	7.5YR 4/6	98.497	40.00	27.39	32.61					
235-260	250	-47.3	7.5YR 4/6	26.878	12.80	42.16	45.04					
235-260	260	-57.3	7.5YR 4/6	27.751	9.97	44.76	45.27					X
260-275	275	-72.3	7.5YR 5/4	48.853	23.10	55.51	21.39					X
275-282	282	-79.3	10YR 6/4 & 7.5YR 4/6	33.934	23.20	51.33	25.47					X
282-290	290	-87.3	7.5YR 4/4 & Gley 6/10Y	96.368	43.89	37.22	18.89				X	
290-300	300	-97.3	Gley 6/10Y & 7.5YR 6/4	36.939	16.33	59.12	24.55					X
	Hole 27											
	C14 sample	Wet	10YR 3/4	32.425	14.21	66.23	19.56					
	Hole 18											
0-18	10	189	7.5YR 4/4	158.745	79.92	13.10	6.98					
18-21	20	179	10YR 3/3	39.015	15.27	47.80	36.93					
21-32	30	169	7.5YR 4/3	139.713	67.19	22.40	10.41					
32-74	40	159	7.5YR 4/3	52.923	25.12	58.64	16.25					
	60	139	7.5YR 4/3	19.274	2.79	75.11	22.11					
	70	129	7.5YR 4/4	35.335	14.43	57.11	28.46					
74-153	80	119	2.5Y 6/1	95.805	55.54	34.20	10.26					
	96	103	2.5Y 5/3	35.599	13.94	59.46	26.60					
	112	87	10YR 5/2	118.781	73.77	20.93	5.31					
	114	85	7.5YR 5/3 & 5/4	172.049	86.48	8.71	4.81					
	118	81	10YR 5/2 & 5/3	127.531	75.17	19.33	5.49					
	121	78	10YR 5/3	160.378	78.39	17.13	4.48					
140-142	142	57	7.5YR 6/4	18.547	10.65	42.21	47.15					
147-148	146	53	2.5Y 6/2	33.76	16.83	63.18	19.99					
	150	49	2.5Y 6/2	83.427	61.57	30.61	7.83					
153-157?	155	44	10YR 5/3	181.083	66.57	23.46	9.97		X			

Layers cm	Sample depth cm	LHD	Munsell colour	Average grain size	% Sand	% Silt	% Clay	Granules	Pebbles	Cobbles	Palaeosol	Gypsum
157-160.5	160	39	7.5YR 4/4	81.146	27.42	41.62	30.95					X
	168	31	10YR 5/4	87.846	48.89	32.01	19.09					
	181	18	7.5YR 5/4	131.36	68.36	24.55	7.09					
162-186	185	14	10YR 5.5/4	204.76	76.94	14.97	8.09					
186-205.5	188	11	10YR 5/3	193.479	81.71	13.08	5.22					
195	195	4	10YR 5/3	227.469	85.98	9.77	4.25					
205-215	205	-6	7.5YR 5/6 & 5/4	222.608	83.47	11.51	5.03					X
	209	-10	10YR 6/6	111.94	55.32	32.57	12.11					
	210.5	-11.5	7.5YR 5/4	101.271	43.58	41.57	14.85					
	211.5	-12.5	10YR 6/6	82.625	34.54	35.78	29.68					X
	213	-14	10YR 5.5/3	111.906	46.68	34.66	18.66					X
	215	-16	7.5YR 5/4 & 5/3	161.541	67.70	22.94	9.36					
216-227	216	-17	7.5YR 5/4	187.765	64.31	24.01	11.68	X	X			
227-232	227	-28	7.5YR 5/4	159.506	73.05	16.73	10.22	X	X			
232-245	232	-33	7.5YR 5/4	198.63	65.76	23.11	11.13	X	X			
	Hole 17											
0-43	8	193.8	7.5 YR 4/4	164.673	74.48	16.64	8.87					
	18	183.8	7.5YR 4/6	147.827	81.28	12.05	6.67					
	40	161.8	5YR 4/4	150.127	69.70	19.10	11.20					
43-53	47	154.8	5YR 3.5/4	55.679	34.49	43.16	22.35					
53-84.5	66	135.8	7.5YR 4/6	193.173	92.55	4.98	2.47					
	82	119.8	7.5 YR 4/4	195.867	75.21	16.14	8.65					
84.5-109	88	113.8	2.5Y 5/4	112.331	55.79	29.81	14.40					
	94	107.8	2.5Y 5/2	71.191	34.31	45.92	19.77					
	107	94.8	10YR 6/2	200.294	90.77	6.91	2.32					
108-109	109	92.8	10YR 6/3	83.333	57.82	33.34	8.84					
127-215	133	74.8	10YR 5.5/3	213.14	93.67	4.65	1.69					
	140.5	61.3	10YR 5/3	111.445	72.05	22.14	5.81					
	160.75	41.05	10YR 5.5/2	78.805	65.87	27.27	6.86					
	172.75	29.05	7.5YR 4.5/4	88.679	55.24	32.46	12.30					
	182.5	19.3	7.5YR 5/2 & 5/3	201.913	91.79	6.50	1.71					
	208.75	-6.95	7.5YR 5/2 & 5/3	196.853	89.65	7.67	2.68					
?-215	214	-12.2	7.5 YR 4/4	89.959	48.07	32.12	19.81					
215-235	215	-13.2	7.5 YR 4/4	47.096	17.45	57.61	24.95					
	235	-33.2	7.5YR 4/4	102.18	43.13	34.16	22.70					
248	248	-46.2	7.5 YR 4/4	78.488	43.91	39.00	17.08				X	
255	255	-53.2	7.5 YR 4.5/6	122.162	54.36	23.49	22.15				X	
290-295	290	-88.2	7.5YR 5/4	90.699	39.12	44.20	16.68				X	

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Layers cm	Sample depth cm	LHD	Munsell colour	Average grain size	% Sand	% Silt	% Clay	Granules	Pebbles	Cobbles	Palaeosol	Gypsum
	Hole 16											
95-105	95	208.6	7.5YR 6/4	469.385	94.63	3.78	1.59	X				
105-125	115	188.6	7.5YR 5/4	102.884	61.48	27.77	10.75					
125-140	125	178.6	7.5YR 4.5/4	121.833	75.07	16.51	8.42	X				
140-175	175	128.6	5YR 4/4	156.001	76.00	16.35	7.65	X			X	
200	200	103.6	7.5YR 4.5/4	229.97	89.22	6.40	4.39					
200-215	203	100.6	7.5YR 4.5/6	191.752	69.46	26.48	4.06					
200-215	210	93.6	7.5YR 4.5/6	189.483	72.92	23.29	3.79					
215-232	216.5	87.1	7.5YR 4.5/6	264.361	72.67	23.82	3.51					
215-232	222	81.6	7.5YR 4.5/6	268.752	69.52	26.12	4.36	X				
215-232	230	73.6	7.5YR 4.5/4	194.095	74.27	20.32	5.41					
237		66.6		250.119	77.75	18.63	3.62					
243-245	245	58.6	7.5YR 4.5/4	326.801	94.17	5.36	0.47					
245-255	251	52.6	7.5YR 4.5/4	366.229	92.55	6.55	0.90	X				
255	255	48.6	7.5YR 4.5/4	359.281	90.33	8.63	1.04					
255-297	263	40.6	7.5YR 5/3 & 5/2	75.876	59.04	29.93	11.02					
255-297	268	35.6	7.5YR 4.5/4	134.432	72.28	21.64	6.09					
255-297	273.5	30.1	7.5YR 4.5/3	259.973	95.31	3.34	1.35					
297-300	298	5.6	7.5YR 5.5/4	250.855	89.12	8.01	2.87	X				
300.5-309	303	0.6	5YR 4/4	48.411	22.33	56.07	21.61					
309-313	311	-7.4	5YR 4/4	87.758	63.13	27.20	9.67					
317	317	-13.4	5YR 4/4	204.791	76.09	15.14	8.77	X				
	Hole 24											
7-24	15	199.6	7.5YR 4/6	153.935	78.51	13.73	7.76					
24-35	30	184.6	7.5YR 5/4	167.891	64.56	24.64	10.81				X	
35-47	40	174.6	7.5YR 5/4	337.96	86.07	10.16	3.76	X				
47-80	50	164.6	10YR 7/3	118.035	55.26	28.54	16.20				X	
	59	155.6	10YR 5/3	60.253	35.13	51.31	13.57					
140	140	74.6	7.5YR 4/6	85.56	43.54	32.30	24.16					
280-282	280	-65.4	5YR 4/4	68.844	26.88	37.78	35.34					
287	287	-72.4	7.5YR 4/6	49.004	21.28	35.78	42.95					
	Hole 19											
0.9-25	6.9	200.4	7.5YR 4/4	146.212	76.64	14.62	8.73					
	19.58	187.72	5YR 4/4	160.489	79.26	13.75	6.98				X	
19-31	26.3	181	7.5YR 6/4	127.339	57.26	21.00	21.74					
40-61	51.84	155.46	10YR 5/3	113.28	64.08	24.27	11.65					
67-69	66.8	140.5	7.5YR 5/4	84.785	42.12	29.80	28.08					
80-84	85.2	122.1	2.5Y 5/3	97.383	51.59	37.48	10.93					
103-115	104.8	102.5	2.5Y 5/3	70.512	36.42	49.74	13.84					

Layers cm	Sample depth cm	LHD	Munsell colour	Average grain size	% Sand	% Silt	% Clay	Granules	Pebbles	Cobbles	Palaeosol	Gypsum
117-122	118.7	88.6	10YR 5/2	195.897	83.93	12.36	3.71					
129-148	132	75.3	2.5Y 5/3	97.001	49.74	34.90	15.36					
148-214	152	55.3	10YR 5/3	122.166	93.93	4.13	1.94					
	200	7.3	7.5YR 5/3 & 5/4	183.239	92.90	4.86	2.24					
219-226	222	-14.7	7.5YR 4/6	163.187	64.85	25.39	9.76	X				
226-234	227	-19.7	7.5YR 5/3	365.036	91.34	5.98	2.68	X				
234-280	242	-34.7	7.5YR 4/4	153.44	63.86	24.90	11.24					
	267	-59.7	5YR 4/6	171.655	57.53	31.17	11.31					
	276	-68.7	5YR 4/6	233.832	63.30	26.01	10.68	X				
280	280	-72.7	5YR 4/4	118.972	51.29	25.91	22.79					
	Hole 21											
0-10	10	185.5	7.5 YR 4/4	95.125	50.95	31.20	17.85					
10-24	15	180.5	10YR 6/2 & 4/4 & 4/6	147.301	82.66	13.36	3.98					
24-30	25	170.5	10YR 5/3	109.733	70.26	26.32	3.42					
128-152	140	55.5	10YR 5/2	70.075	37.99	46.26	15.75					
152-160	152	43.5	10YR 5/3	153.699	48.03	28.07	23.90	X				
170	170	25.5	7.5YR 5/3	199.758	56.41	27.97	15.62		X			
180												
	Hole 20											
0-23	8	193.8	7.5 YR 4/4	168.157	79.71	13.83	6.45					
24-29	28	173.8	7.5 YR 5/4	150.082	77.14	16.99	5.87				X	
29-40	29.5	172.3	7.5 YR 4/1	48.985	16.51	57.44	26.06					
29-40	34	167.8	7.5 YR 5/2	130.745	72.26	17.97	9.77				X	
40-125	45	156.8	10YR 3/3	144.822	75.59	14.63	9.78					
150-170	150	71.8	10YR 5/3	126.189	76.46	15.42	8.11					
205-210	205	-3.2	7.5 YR 4.5/4	184.773	80.75	12.76	6.49	X				
210-215	210	-8.2	7.5 YR 4/4	322.556	77.87	15.23	6.91	X				
215	215	-13.2	7.5 YR 4/3	258.977	75.39	17.10	7.51	X				
	Hole 22											
60-63	61	172.2	10YR 5/4	110.331	62.92	24.37	12.71					
65-69	67	166.2	7.5 YR 4/4	97.833	75.50	17.16	7.34					
88-100	88	145	5YR 4/4	169.683	75.49	17.34	7.16	X	X			
	Hole 23											
5-36	20	333.1	7.5 YR 6/4	218.381	84.91	11.72	3.37				X	
36-53	45	308.1	7.5 YR 6/4	334.135	91.81	6.09	2.09		X			
89-92.5	90	263.1	10 YR 6/4	218.236	82.73	12.88	4.39				X	
117-142	141.2	211.9	10 YR 6/4	188.779	84.40	11.62	3.98					
	Hole 28											
0-140	30	327.9	7.5 YR 6/4	253.239	96.79	1.83	1.38					

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Layers cm	Sample depth cm	LHD	Munsell colour	Average grain size	% Sand	% Silt	% Clay	Granules	Pebbles	Cobbles	Palaeosol	Gypsum
	Hole 29											
30-72	44	173.2	5YR 4/6	25.104	9.33	59.93	30.73					
	54	163.2	5YR 4/4	29.922	13.22	56.82	29.96					
	65	152.2	5YR 4/6	55.52	25.63	44.29	30.08				X	
	Hole 32											
	Upper		7.5 YR 4/6	170.728	87.02	9.03	3.95					
	Mid		7.5 YR 4/4	91.03	51.71	29.94	18.35					
	Lower		5YR 4/4	131.117	69.09	21.49	9.42					
	Hole 33											
	10	203.9	5Y 6/2	42.429	56.46	30.11	17.69					
	Hole 30											
180-183	183	179.9	7.5YR 5/6	133.415	55.05	26.70	18.25				X	
183-195	194	168.9	7.5YR 4.5/4	69.724	45.68	34.47	19.85					
197-210	198	164.9	7.5YR 4/6	91.307	57.31	27.95	14.74					
210	208	154.9	7.5YR 4/6	50.425	31.42	48.25	20.33					
250-300	262	100.9	7.5YR 4.5/4	257.392	89.61	7.10	3.29					
	282	80.9	7.5YR 4.5/4	309.38	96.23	2.95	0.82					
	288	74.9	7.5YR 4.5/4	317.771	97.37	1.87	0.76					
300-304	302	60.9	7.5YR 4.5/4	314.829	92.58	5.64	1.78	X				
304-307		58.9		280.054	90.59	6.20	3.21					
307-316	309	53.9	5Y 6/2 & 7.5YR 5/4	175.104	54.08	28.99	16.93		X			
316-319	318	44.9	2.5Y 5.5/3	12.144	1.80	65.14	33.06		X			
319-322.5	322	40.9	7.5YR 5/4	287.366	65.45	24.27	10.28	X	X			
322.5-325	325	37.9	5Y 6/2	30.704	17.00	54.01	29.00					
325-345	336	26.9	2.5Y 5/3	67.341	18.05	51.21	30.74				X	
348.5-352	350	12.9	2.5Y 6/1	76.783	36.96	41.93	21.11					
352	352	10.9	5Y6/2	46.759	22.39	47.80	29.81					
353	353	9.9	5Y6/2	49.779	22.82	48.32	28.86					
	Yardangs											
	Y1		7.5YR 6/6	164.572	91.01	6.35	2.64					
	Y2		7.5YR 6/4	141.422	89.01	8.11	2.89					
	Dunes											
	D1		7.5YR 5.5/6	195.723	97.50	1.91	0.59					
	D2		7.5YR 5.5/6	256.611	98.13	1.67	0.20					
	D3		7.5YR 5.5/6	251.242	97.99	1.80	0.21					

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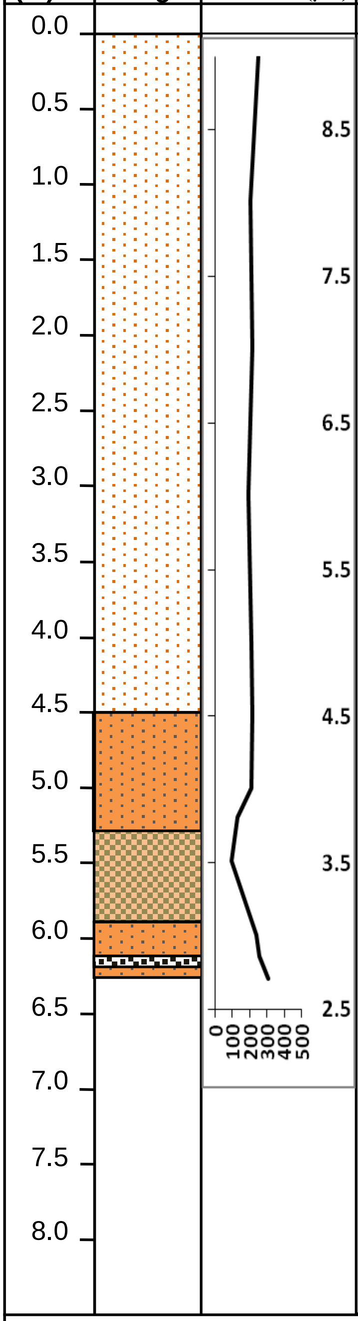
APPENDIX 4.4: STRATIGRAPHIC LOG TRANSECT A

Lake Frome shoreline Hole: 12 Location (Zone 54): 368815, 6611445 Elevation (local relative height): + 9.01 m	**Geochronology Data**

Depth (m)	Core Log	LHD (m) Grain size (µm)	Description	Environment of Deposition
			Massive dune sands.	Aeolian
			Fluvial sands.	Fluvio-deltaic deposition
			Palaeosol with gypcrete/calcrete development.	Insitu or transported
			Fluvial sands. Gravel layer – granules to 0.8cm.	Fluvio-deltaic deposition

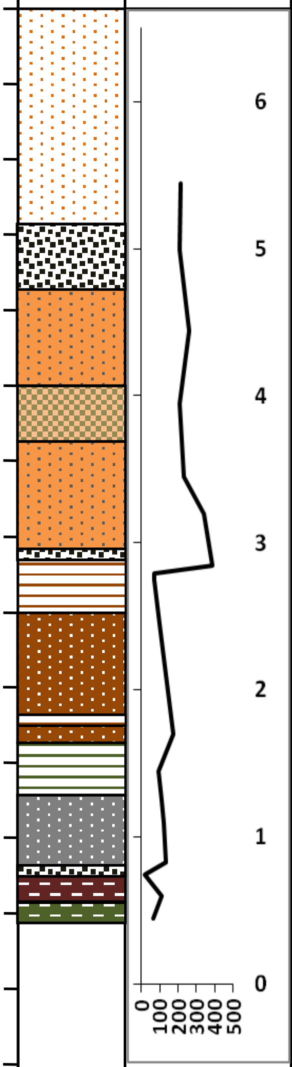


Lake Frome shoreline

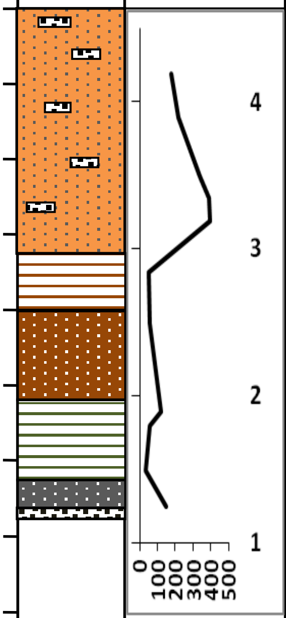
Hole: 13
Location (Zone 54): 368824, 6611426
Elevation (local relative height): + 6.45 m

Geochronology Data

Depth (m)	Core Log	Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0				
0.5			Massive dune sands.	Aeolian
1.0				
1.5			Fluvial sands with gravel – granules & pebbles to 6cm.	Fluvio-deltaic deposition – bar formation in gravel
2.0			Fluvial sands.	
2.5			Palaeosol with gypcrete/calcrete development.	Insitu or transported
3.0			Fluvial sands fining up.	Fluvio-deltaic
3.5			Gravel layer – pebbles to 1cm.	
4.0			Red-brown silt.	Prodelta/lacustrine
4.5			Red-brown sand. Thin silt lamination. Red-brown sand.	Prodelta/lacustrine
5.0			Gray-blue silt with oxidised sands.	Fluvio-deltaic
5.5			Gray sands fining up. Gravel layer – pebbles to 2.5cm.	Lacustrine
6.0			Thick units of silt.	
6.5				
7.0				
7.5				
8.0				

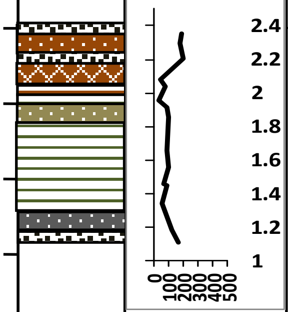


Lake Frome shoreline Hole: 14 Location (Zone 54): 368847, 6611399 Elevation (local relative height): + 4.49 m	**Geochronology Data** TL date of 11.5 $\pm$ 0.7ka at 50cm depth TL date of 16.7 $\pm$ 0.9k at 120cm depth

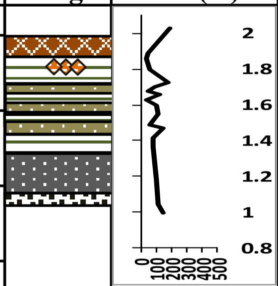


Depth (m)	Description	Environment of Deposition
0.0		
0.5	Fluvial sands fining up with granules throughout – granules & pebbles to 2.75cm.	Fluvio-deltaic
1.0	Pebbles coated in a carbonate crust.	
1.5		
	Red-brown silt.	
2.0		Prodelta/lacustrine
	Oxidised sands.	
2.5		Shallow lacustrine
	Silt with oxidization mottling.	Fluvio-deltaic
3.0		
	Gray sands fining up.	
3.5	Gravel layer – granules and pebbles to 3.5cm.	
4.0		
4.5		
5.0		
5.5		
6.0		
6.5		
7.0		
7.5		
8.0		

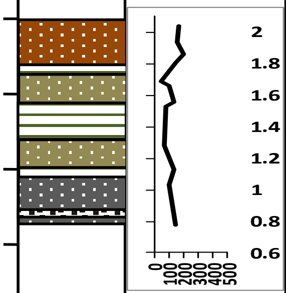
Lake Frome lake floor Hole: 11 Location (Zone 54): 368846, 6611377 Elevation (local relative height): + 2.41 m	**Geochronology Data**

Depth (m)	Core Log	Grain size (µm) LHM (m)	Description	Environment of Deposition
0.0			Surface pebble layer.	Sheet wash/erosion
			Red-brown sands above gravel – pebbles to 3cm.	Sheet wash/erosion
			Red-brown sands fluffed by gypsum.	Ephemeral playa
0.5			Oxidised sands fining up to thin silty horizons.	
			Gray-green silts & very fine sands mottled with oxidization.	Margins of delta & shallow lacustrine
1.0				
			Fine gray sand.	
1.5			Gravel layer – pebbles to 5cm.	Fluvio-deltaic
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

Lake Frome lake floor Hole: 3 Location (Zone 54): 368850, 6611373 Elevation (local relative height): + 2.04 m	**Geochronology Data** TL date of 80.8 $\pm$ 5.4ka at 35cm depth

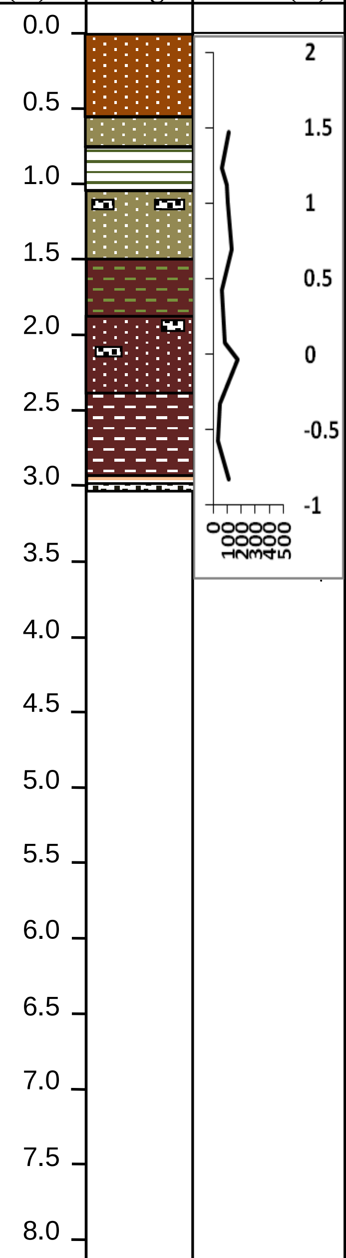
Depth (m)	Core Log	Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0			Red-brown sands - seed gypsum below 3cm. Thin layers of gray-green silts (selinite shard at 16-17cm) & oxidised sands.	Ephemeral playa Margins of delta & shallow lacustrine
0.5				
1.0			Fine gray sands fining up. Gravel layer – pebbles to 5cm.	Fluvio-deltaic
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

Lake Frome lake floor Hole: 1 Location (Zone 54): 368853, 6611358 Elevation (local relative height): + 2.09 m	**Geochronology Data**

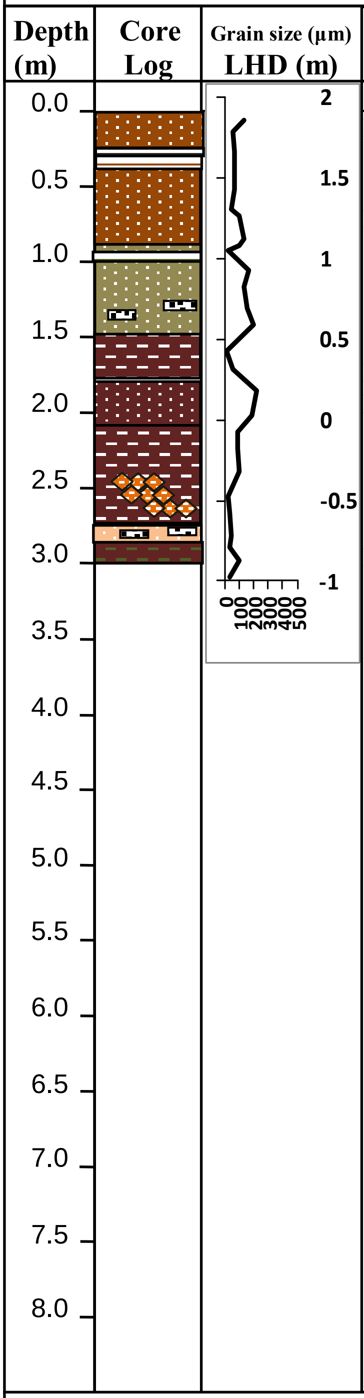


Depth (m)	Core Log	Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0			Red-brown sands - thin laminations of white salts.	Ephemeral playa
0.5			Thin layers of gray-green silts & oxidised sands.	Margins of delta & shallow lacustrine
1.0			Fine gray sands fining up.	Fluvio-deltaic
			Gravel layer – pebbles to 5.5cm.	
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

Lake Frome lake floor Hole: 15 Location (Zone 54): 368877, 6611308 Elevation (local relative height): + 2.08 m	**Geochronology Data**

Depth (m)	Core Log / Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0 – 0.5		Red-brown sands - thin laminations of white salts.	Ephemeral playa
0.5 – 1.0		Thin layers of gray-green silts & very fine oxidised sands.	Margins of delta & shallow lacustrine
1.0 – 1.5		Pebble granules to 0.7cm.	
1.5 – 2.0		Red-brown clay mottled with olive green clay.	Lacustrine followed by oxidisation
2.0 – 2.5		Red-brown sands with pebble granules.	Lacustrine
2.5 – 3.0		Thick red-brown clay.	
3.0		Thick sandy silt with granules and gravel – pebbles to 3.5cm (flat river-bed pebble).	Fluvio-deltaic

Lake Frome lake floor Hole: 2 Location (Zone 54): 368904, 6611241 Elevation (local relative height): + 2.03 m	**Geochronology Data**



Description	Environment of Deposition
Red-brown sands. Grey & red-brown silt layers.	Ephemeral playa Localised ponding
Red-brown sands. Gray-green silt.	Ephemeral playa Localised ponding
Thin layers of oxidised sands – pebble granules.	Margins of delta
Red-brown silt. Red-brown sands with pebble granules.	Lacustrine followed by oxidisation
Thick red-brown clay and silt with carbonate.	Near shore lacustrine
Thick tan silt, pebble granules to 0.7, selinite. Mottled red-brown and gray-green silt and very fine sand, selinite.	Near shore lacustrine

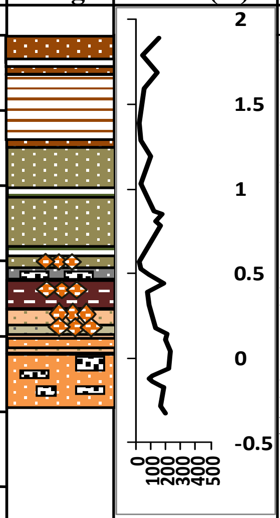
Lake Frome lake floor

Hole: 18
Location (Zone 54): 368941, 6611154
Elevation (local relative height): + 2.00 m

Geochronology Data

Depth (m): 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0

Core Log | Grain size (µm) LHD (m)

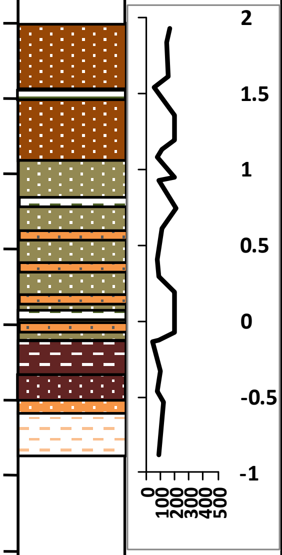


Description	Environment of Deposition
Red-brown sands. Grey & red-brown silt layers.	Ephemeral playa Localised ponding
Laminations of lightly oxidised gray sands fining up with thin clay layers.	Inner margins of fluvial delta
Gray sands with pebbles to 2.3cm. Red-brown sand and silt fining up. Tan sand and silt in hardened layers – mixed light tan and yellow colours.	Fluvio-deltaic Lacustrine
Fluvial sands with abundant granules and pebbles to 4.5cm.	Fluvio-deltaic

Lake Frome lake floor

Hole: 17
Location (Zone 54): 368968, 6611085
Elevation (local relative height): + 2.02 m

Geochronology Data

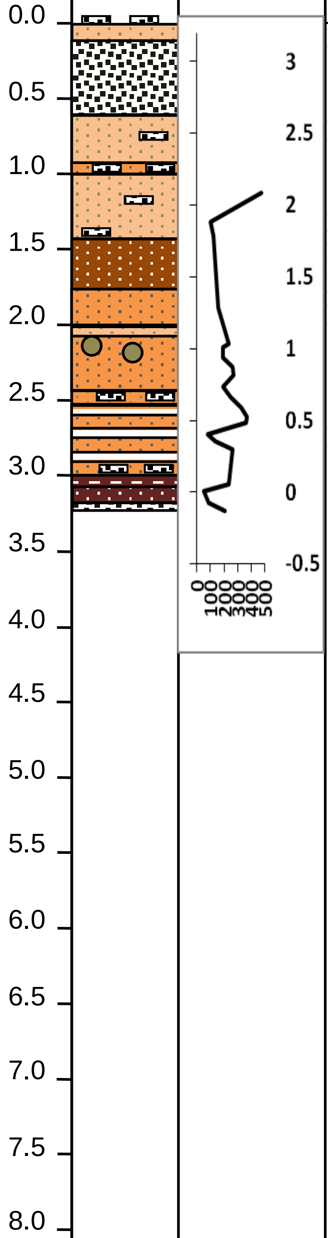
Depth (m)	Core Log	Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0				
			Red-brown sands.	Ephemeral playa
0.5			Red-brown clay.	Localised ponding
1.0			Pulses of oxidised gray sands and fine clay lenses.	Fluvio-deltaic pulses shallow and/or fluctuating lake levels
1.5			Laminations of clean fluvial sands and oxidised sand bands in many pulses - fining up to very fine sands or very fine silt layers.	
2.0				
2.5			Red-brown silt and sand.	Lacustrine followed by oxidisation
			Tan silt and sand with carbonate development.	Nearshore lacustrine
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

Lake Frome palaeodelta

Hole: 16
Location (Zone 54): 368992, 6611036
Elevation (local relative height): + 3.04 m

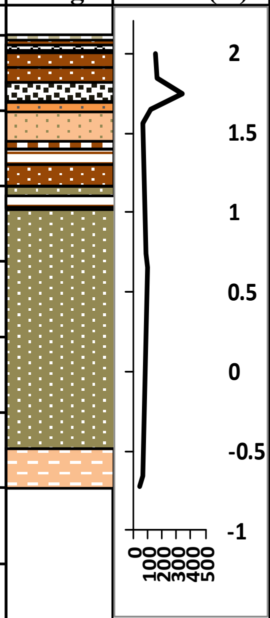
Geochronology Data
TL date of 92.4 ± 6.2ka at 237cm depth

Depth (m) | **Core Log** | Grain size (µm) **LHD (m)**



Description	Environment of Deposition
Dry massive surface sands.	Aeolian / beach
Thick gravel band – pebbles to 6cm.	Fluvio-deltaic mouth or channel bar
Fine/medium massive sands with some pebbles.	Aeolian / beach
Coarser sands with pebbles to 3.5cm.	Fluvio deltaic
Mottled tan sands.	Palaeosol/water table interface?
Red-brown sands.	
Massive sands fining up.	Fluvio-deltaic
Finer massive sands.	
Sands with granules coarsening up from 228cm.	Fluvio-deltaic
Sands of medium coarseness with rip-up clasts - scoured into sandy silt unit below.	Renewed fluvial pulse
Five sequences of sand pulses fining up to thin silty horizons.	Subaqueous fluvio-deltaic pulses
Thick red-brown silt and sand.	Lacustrine
Gravel – granules to 0.35cm and pebbles to 5.5cm.	

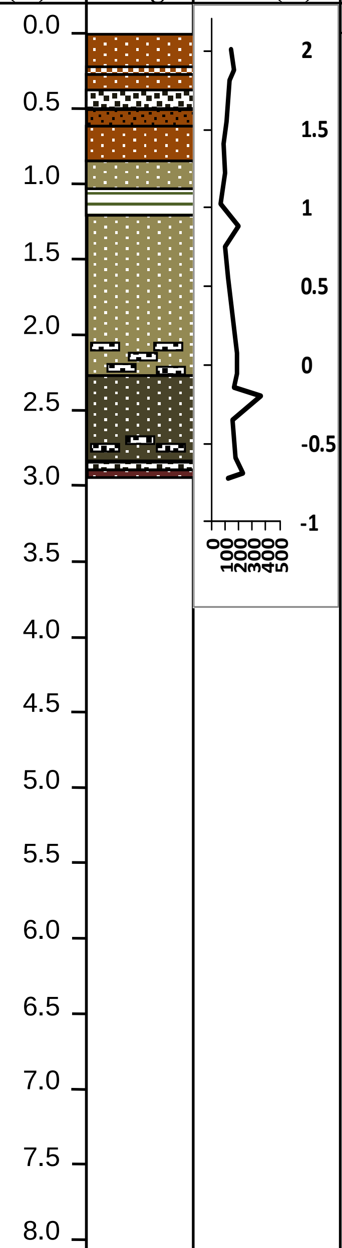
Lake Frome lake floor Core: 24 Location (Zone 54): 369007, 6610978 Elevation (local relative height): + 2.15 m	**Geochronology Data**



Depth (m)	Description	Environment of Deposition
0.0	Surface salts	
	Red-brown surface sands & layer of plant remains.	Ephemeral playa
0.5		Flood deposits or erosion from palaeodeltaic sediments
	Gravel & fluvial sands – granules & pebbles to 3cm.	
1.0	Sandy silt with hard carbonate layer at 50cm.	
1.5	Laminated sand and silt/clay units.	Fluvio-deltaic Lacustrine
2.0		
2.5	Thick orange-brown clay.	Lacustrine
3.0		
3.5		
4.0		
4.5		
5.0		
5.5		
6.0		
6.5		
7.0		
7.5		
8.0		

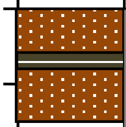
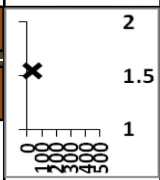
Lake Frome lake floor Core: 19 Location (Zone 54): 369025, 6610910 Elevation (local relative height): + 2.07 m	**Geochronology Data**

Depth (m) | **Core Log** | **Grain size (µm) LHD (m)**



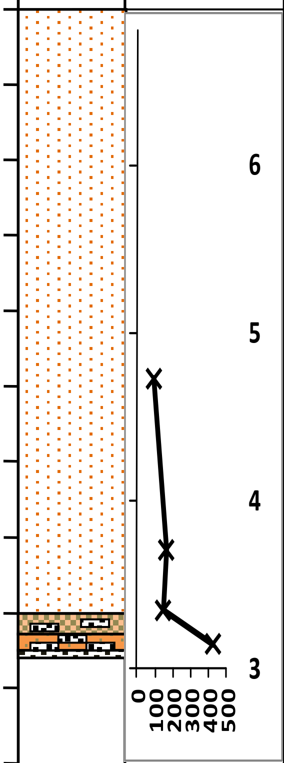
Description	Environment of Deposition
Red-brown surface sands with palaeosol development and pebbles to 4cm in fine sand. Brown sandy silt - black spots possibly manganese or organics. Red-brown sandy silt draped on pale grey-green oxidised sands and silts – manganese or organics.	Ephemeral playa Flood deposits or erosion of palaeodelta Subaqueous fluvio - deltaic pulses
Multiple laminations of oxidised and unoxidised sands and fine layers of silts. Gray sands with granules.	
Massive brown sands with granules.	Fluvio-deltaic
Pebbles in brown sandy silt.	

Lake Frome Lake floor Hole: 27 Location (Zone 54): Elevation (local relative height): + 1.92 m	**Geochronology Data** 14C date of 2,860 $\pm$ 30 at 237cm depth

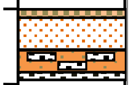
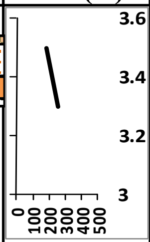
Depth (m)	Core Log	Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0			Layers of red-brown fine sands and sandy silts.	Ephemeral playa
0.5			Silt with organics.	
1.0				
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

APPENDIX 4.5: STRATIGRAPHIC LOG TRANSECT B

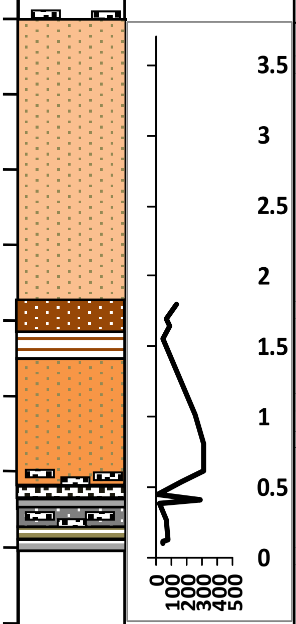
Lake Frome Shoreline Hole: Remnant Dune Location (Zone 54):TL upper - 368272, 6610776 TL lower - 368274, 6610785 Elevation (local relative height): + 6.84 m	**Geochronology Data** TL date of 11.5 $\pm$ 0.7 at 314cm depth

Depth (m)	**Core Log**	**Grain size (µm) LHD (m)**	**Description**	**Environment of Deposition**
0.0			Partially consolidated remnant dune – colonized by plants on upper surface.	Aridity and desiccation followed by ephemeral conditions
0.5				
1.0				
1.5				
2.0				
2.5				
3.0				
3.5				
4.0			Granules in palaeosol – rootlets and carbonate Medium fluvial sands with carbonate coated pebbles.	Fluvio deltaic deposition on upper shoreline
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

Lake Frome Shoreline Hole: 25 Location (Zone 54): 368272, 6610801 Elevation (local relative height): + 3.70 m	**Geochronology Data**

Depth (m)	Core Log	Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0			Remnant dune surface – dune sands continue 30cm. Medium brown sands with pebbles to 4.5cm.	Aridity / ephemeral Fluvio deltaic
0.5				
1.0				
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

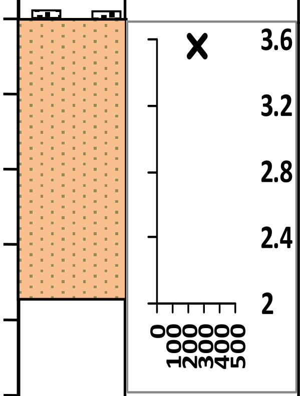
Lake Frome Palaeodelta Hole: 30 Location (Zone 54): 368552, 6610784 Elevation (local relative height): + 3.63 m	**Geochronology Data** TL date of 84.7 ± 5.6 at 276cm depth



Depth (m)	Description	Environment of Deposition
0.0	Granules on surface	
	Massive sands.	Fluvio deltaic
0.5		
1.0		
1.5		
2.0	Red & brown sandy silts.	Palaeosol/water table interface?
2.5	Massive fluvial sands with micas, granules and pebbles to 5cm.	
3.0	Clean sands with fine laminations of gray silts.	Subaqueous fluvio deltaic pulses
3.5	Mixed and mottled silts with pebbles fining down to gray clay.	Lacustrine
4.0		
4.5		
5.0		
5.5		
6.0		
6.5		
7.0		
7.5		
8.0		

Core Log | Grain size (µm) LHD (m)

Lake Frome Palaeodelta Hole: 28 Location (Zone 54): 368568, 6610786 Elevation (local relative height): + 3.63 m	**Geochronology Data**



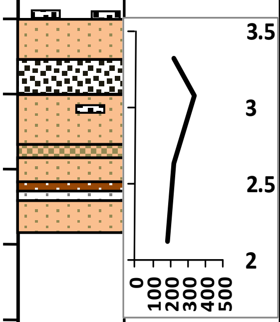
Depth (m)	**Core Log**	**Grain size (µm) LHD (m)**	**Description**	**Environment of Deposition**
0.0			Granules on surface	
0.5			Massive sands.	Fluvio deltaic
1.0				
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

Lake Frome Palaeodelta

Hole: 23
Location (Zone 54): 368968, 6611015
Elevation (local relative height): + 3.53 m

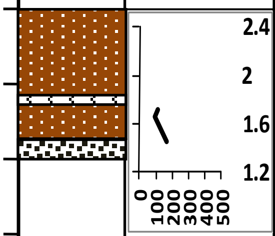
Geochronology Data

Depth (m)	Core Log	Grain size (μm) LHD (m)	Description	Environment of Deposition
0.0			Granules on surface	
			Sands weakly cemented & carbonate concretions.	Palaeosol
			Pebbles to 4.5cm bedded horizontally.	Fluvio deltaic
0.5			Massive sands with floating pebbles.	Fluvio deltaic
1.0			Sands with rootlets and carbonate.	Palaeosol
			Red and white layers of sands.	
			Sands - horizontal laminations – thin black lens (organics?) at 142 & rootlets 137-140.	
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				



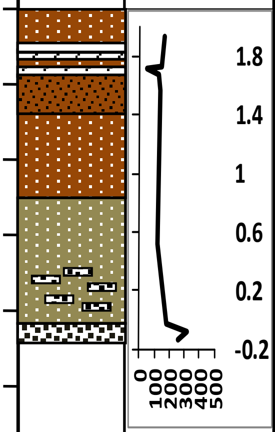
Lake Frome lake floor Hole: 22 Location (Zone 54): 369005, 6611044 Elevation (local relative height): + 2.33 m	**Geochronology Data**

Depth (m)	Core Log	Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0			Red-brown lake floor sands - horizontally laminated.	Ephemeral playa
0.5				Palaeosol development
			Hard carbonate crust.	
1.0			Pebbles to 7cm in fine sand.	Flood deposits or erosion of palaeodelta
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				



Lake Frome lake floor Hole: 20 Location (Zone 54): 369035, 6611061 Elevation (local relative height): + 2.02 m	**Geochronology Data**

Depth (m)	Core Log	Grain size (µm) LHD (m)	Description	Environment of Deposition
0.0 – 0.2			Red-brown lake floor sands - horizontally laminated.	Ephemeral playa
0.5			Thin silt & hard carbonate crust. Thick layers of red-brown sand with black mottling.	Palaeosol
1.0, 1.5				
2.0			Laminations of oxidised and unoxidised sands with granules and pebbles in lower laminations to 2.8cm. Pebbles to 6cm in medium sands.	Margins of delta Fluvio-deltaic
2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0				

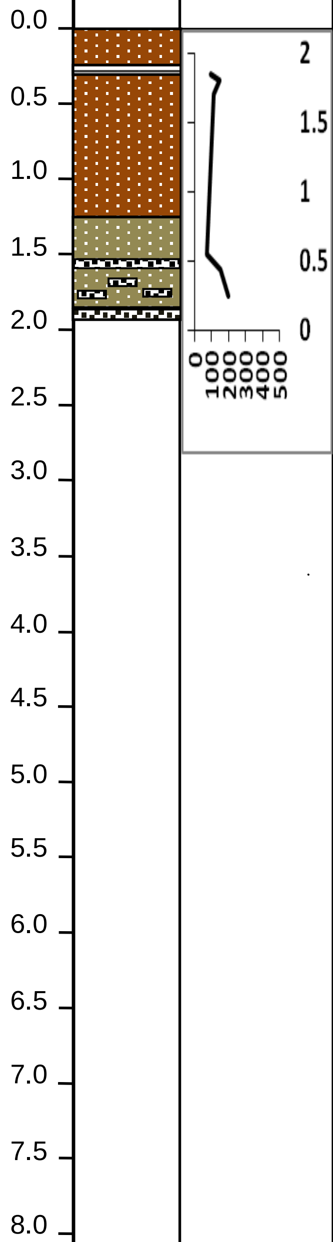


Lake Frome lake floor

Hole: 21
Location (Zone 54): 369162, 6611160
Elevation (local relative height): + 1.95 m

Geochronology Data

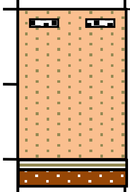
Depth (m)	Core Log	Grain size (µm) LHD



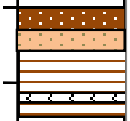
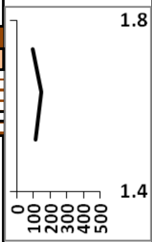
Description	Environment of Deposition
Red-brown lake floor sands - horizontally laminated. Thin silt layer.	Ephemeral playa
Oxidised and unoxidised sands and thin silt lenses.	Margins of delta
Pebbles to 5cm in fine sand. Pebbles to 6cm in fine sand.	Fluvio-deltaic

APPENDIX 4.6: STRATIGRAPHIC LOG TRANSECT C

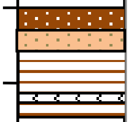
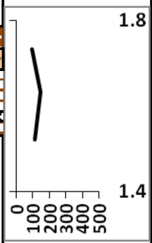
Lake Frome Lake floor Hole: 31 Location (Zone 54): 368553, 6610806 Elevation (local relative height): + 2.7 m	**Geochronology Data**

Depth (m)	**Core Log**	**Grain size (µm) LHD**	**Description**	**Environment of Deposition**
0.0		2.7	Massive sands – floating granules from 0-12cm.	Fluvio deltaic / possible post depositional modification
0.5				
1.0		1.4	Silt/clay horizon. Red-brown sands.	Lacustrine Palaeosol/ water table interface
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

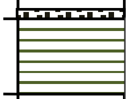
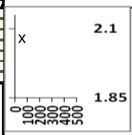
Lake Frome Lake floor Hole: 29 Location (Zone 54): 368550, 6610812 Elevation (local relative height): + 2.17 m	**Geochronology Data**

Depth (m)	Core Log	Grain size (µm) LHD	Description	Environment of Deposition
0.0			Laminations of red, orange and gray sands down core. Red-brown silts. Thin carbonate crust.	Fluvio deltaic / possible post depositional modification Lacustrine Palaeosol
0.5				
1.0				
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

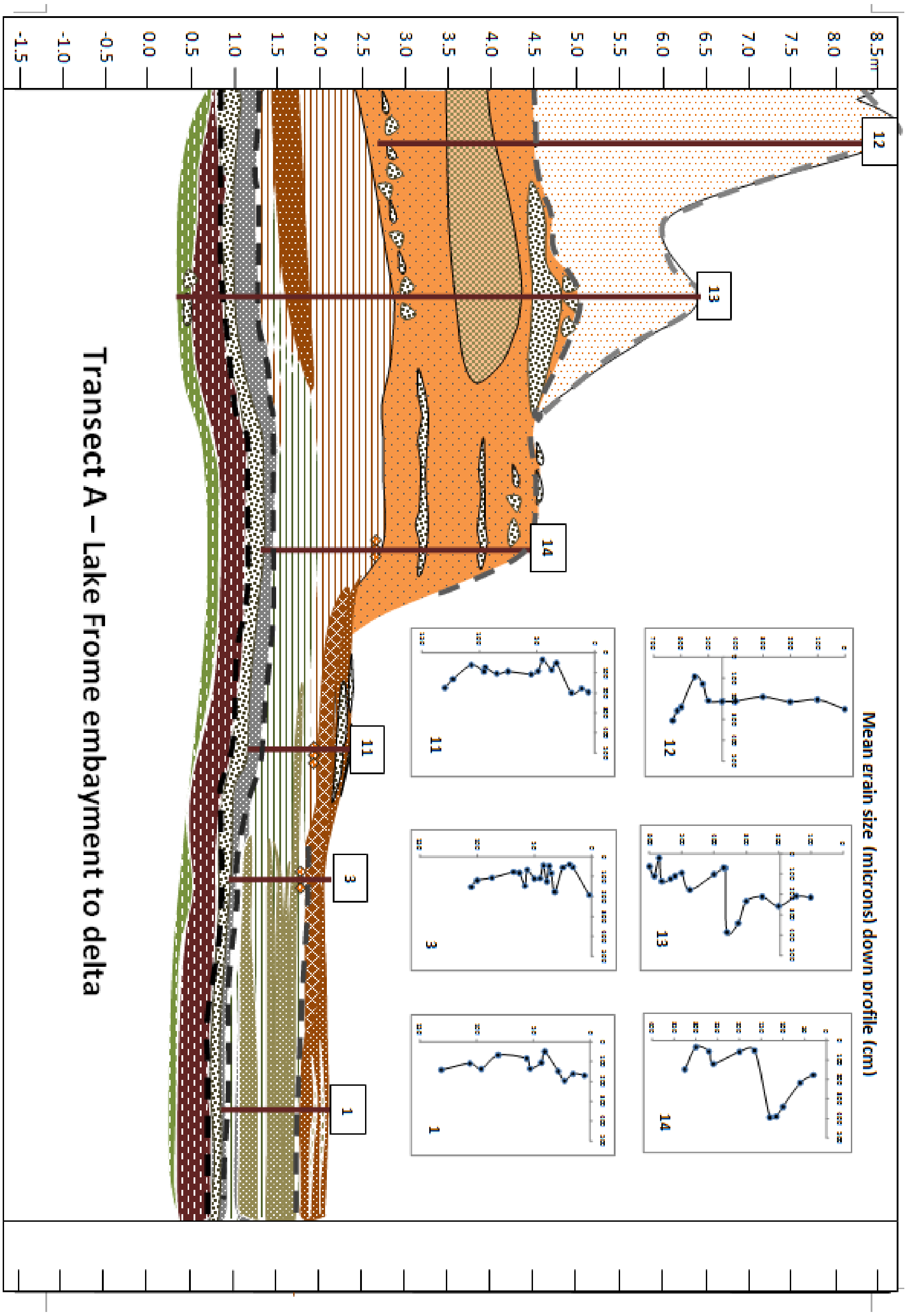
Lake Frome Lake floor Hole: 29 Location (Zone 54): 368550, 6610812 Elevation (local relative height): + 2.17 m	**Geochronology Data**

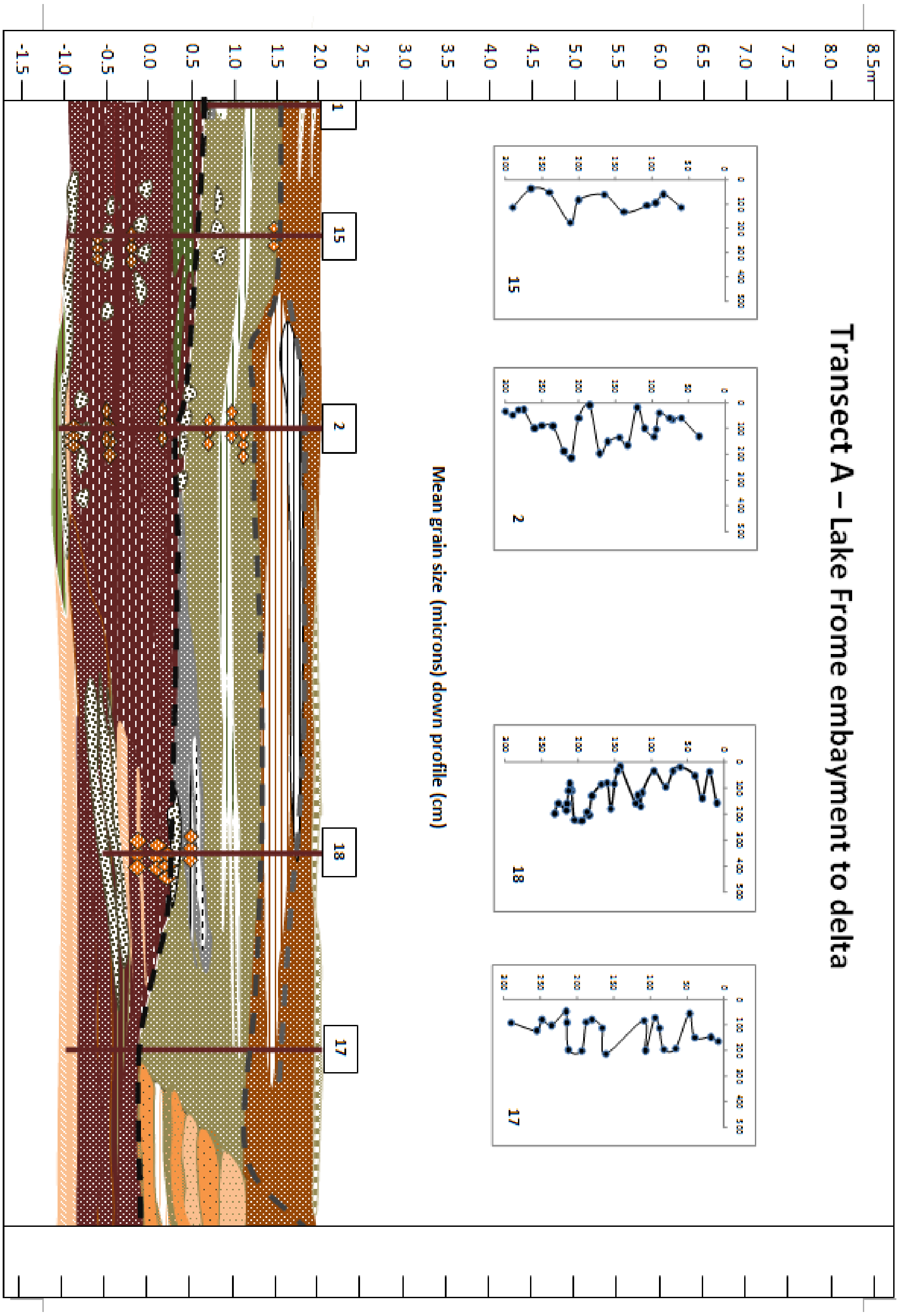
Depth (m)	**Core Log**	**Grain size (µm) LHD**	**Description**	**Environment of Deposition**
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0			Laminations of red, orange and gray sands down core. Red-brown silts. Thin carbonate crust.	Fluvio deltaic / possible post depositional modification Lacustrine Palaeosol

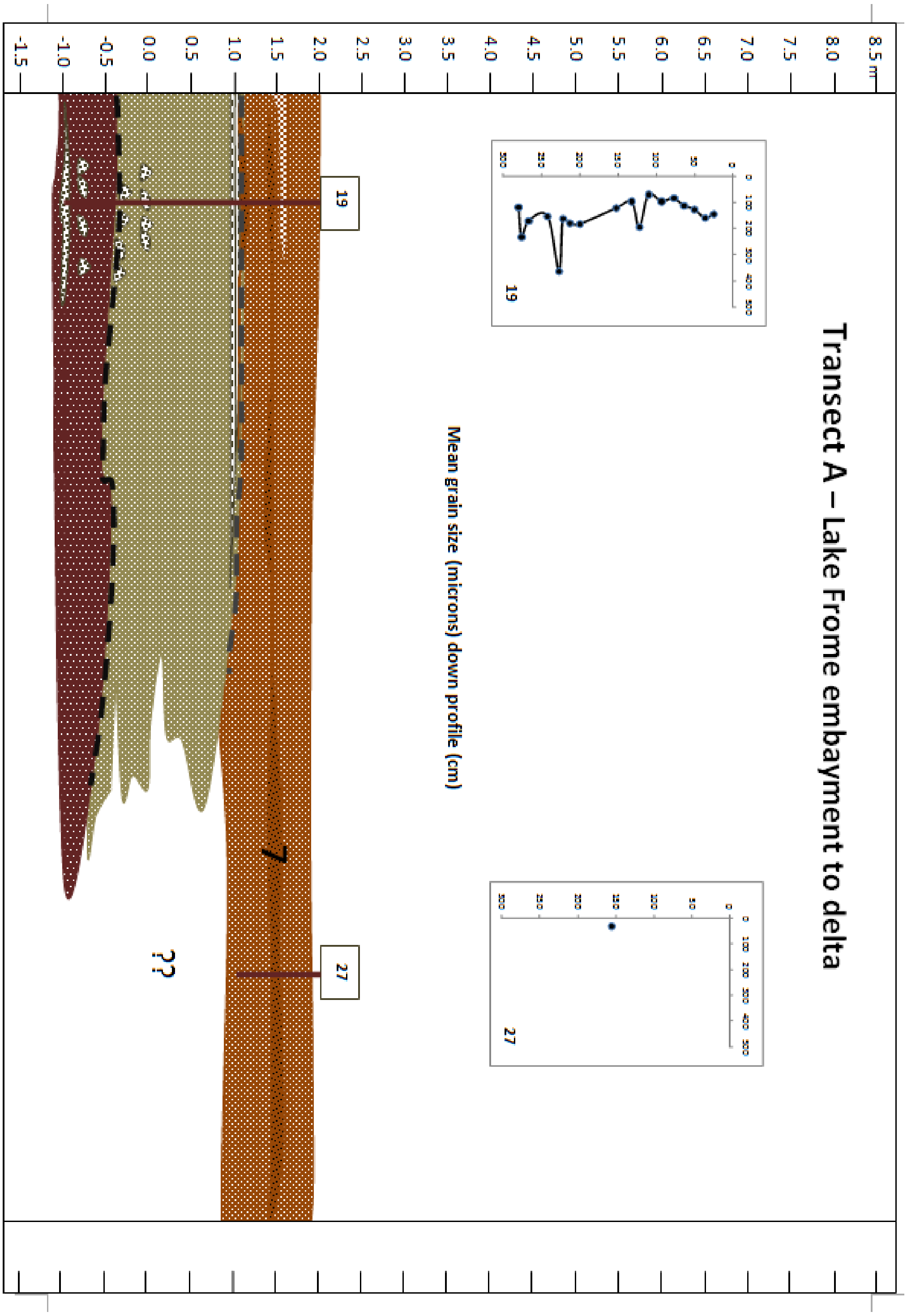
Lake Frome Lake floor Hole: 33 Location (Zone 54): 368556, 6610923 Elevation (local relative height): + 2.14 m	**Geochronology Data**

Depth (m)	**Core Log**	**Grain size (µm) LHD**	**Description**	**Environment of Deposition**
0.0			Pebbles on surface	
			Red-brown surface sands to 5cm Gray-green silt	Pro-delta/lacustrine
0.5				
1.0				
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				
7.5				
8.0				

APPENDIX 4.7: TRANSECT A



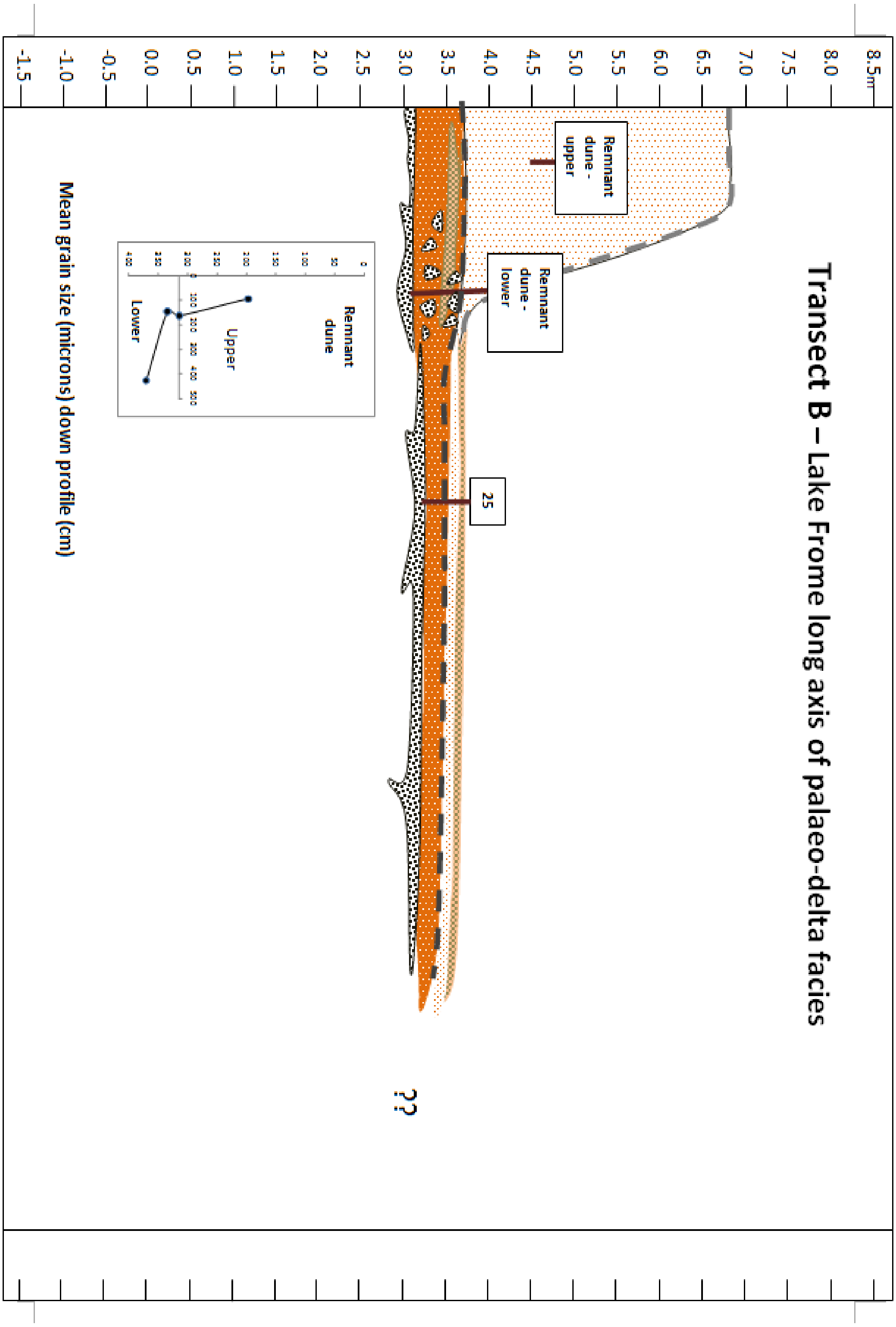

Transect A – Lake Frome embayment to delta
Mean grain size (microns) down profile (cm)
15
2
18
17
1
8.5m
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5

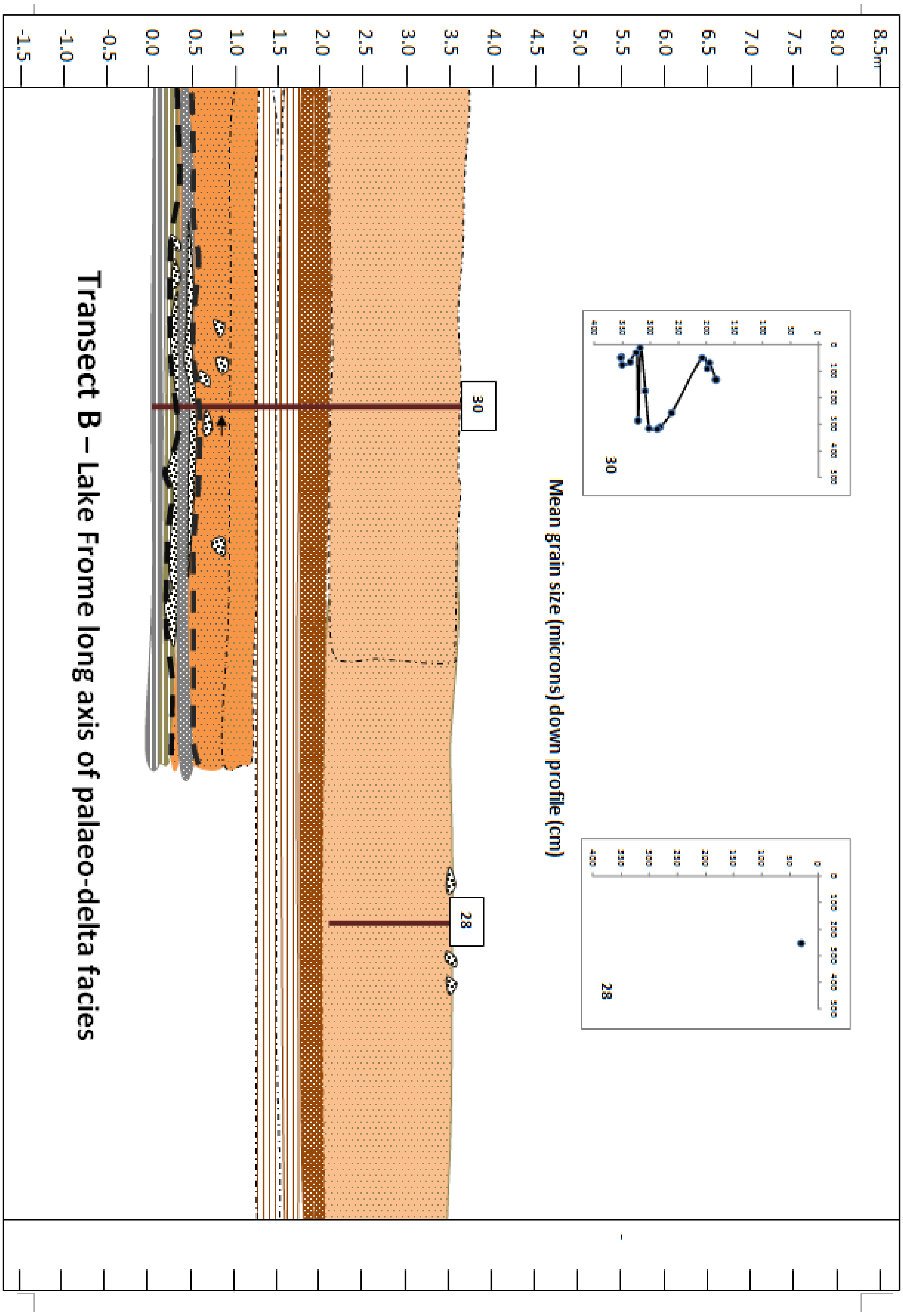

Transect A – Lake Frome embayment to delta
Mean grain size (microns) down profile (cm)
19
27
??
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5 m

Symbol key

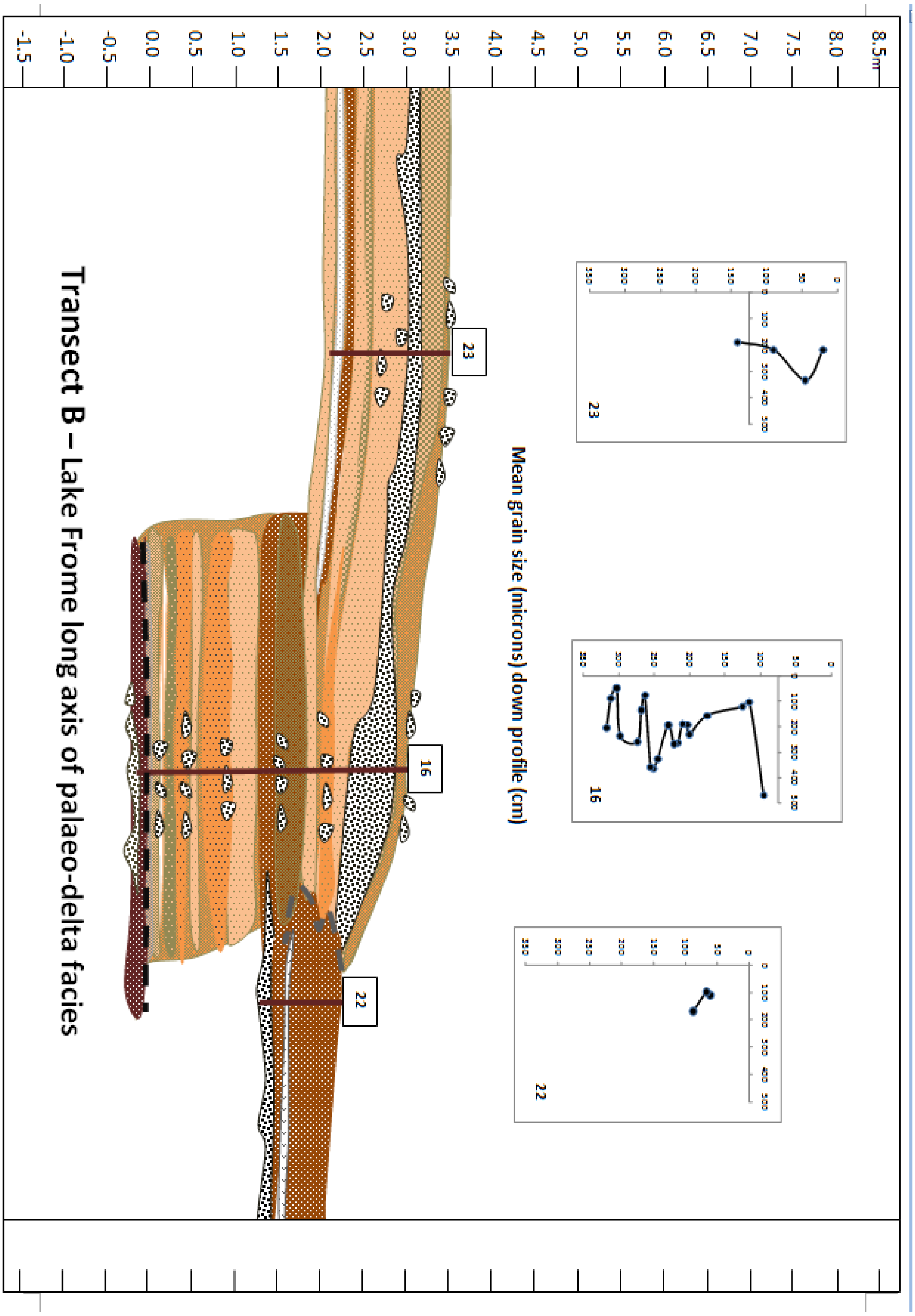
Red-brown loam – horizontal laminations or massive (~70-75% sand)	Fluvio-deltaic pluses - laminations of tan, grey & orange sands – some oxidised
Red-brown sands fluffed by seed gypsum	Aeolian sands
Red-brown silt (~30/40/20 s, s, c)	Palaeosol sands
Gravel – pebbles of cobble size in sand, silt or clay matrix	Thick red-brown clay, silt and sand units
Floating pebbles/pebble granules in sand, silt or clay matrix	Grey-green silt and clay
Laminations of oxidised and un-oxidised sand layers with thin clay lenses – subaqueous deposition	Salt layers
Unoxidised grey sands	Thick orange-tan clay and sandy clay units
Fluvial sands (containing mica and poorly sorted)	Organic remains
Brown & black silts	Gypsum (selinite or rose crystals)
Massive very fine to medium sands	Carbonate and clay – nearshore lacustrine

APPENDIX 4.8: TRANSECT B

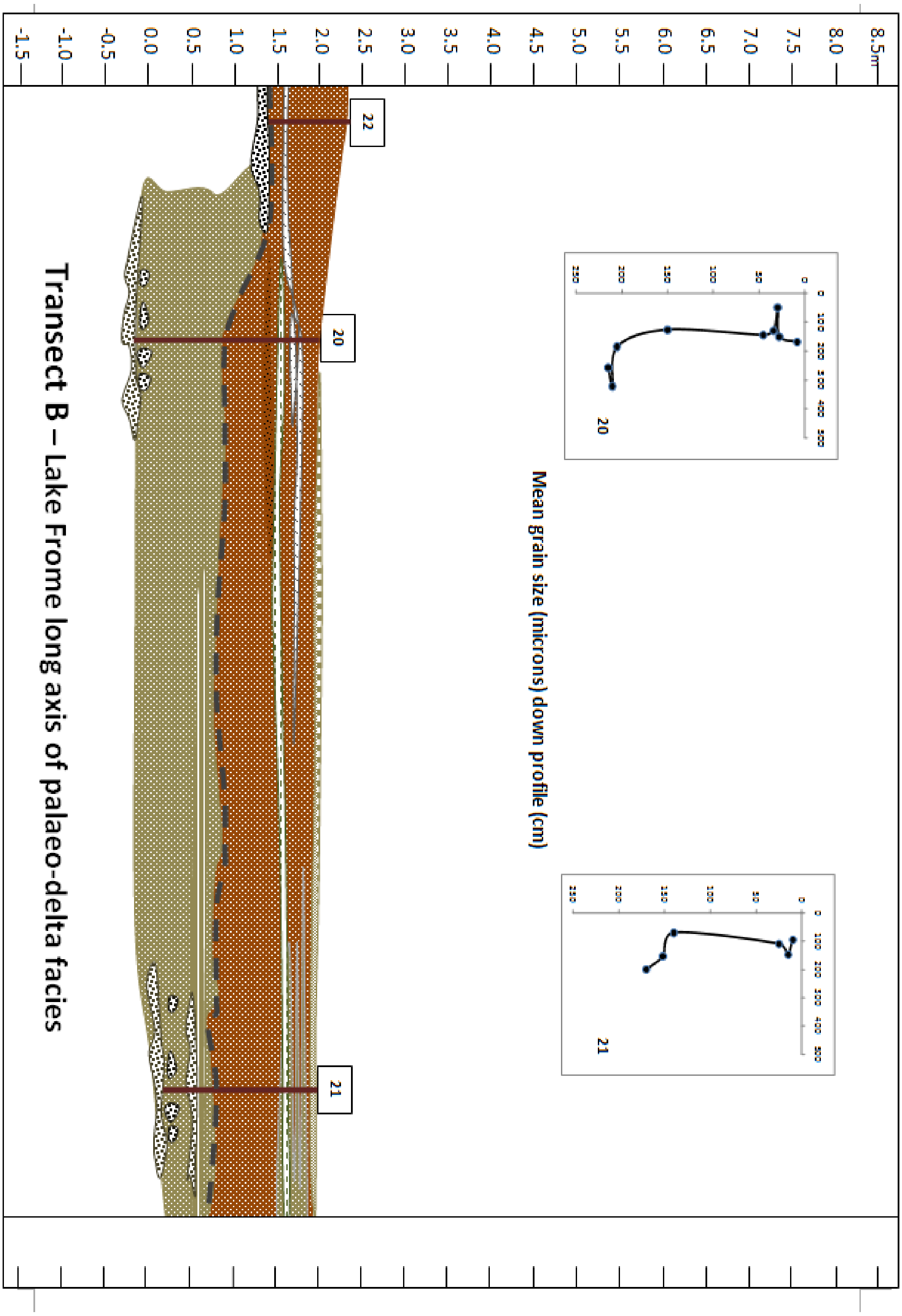




Transect B – Lake Frome long axis of palaeo-delta facies
Mean grain size (microns) down profile (cm)
30
28
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5m

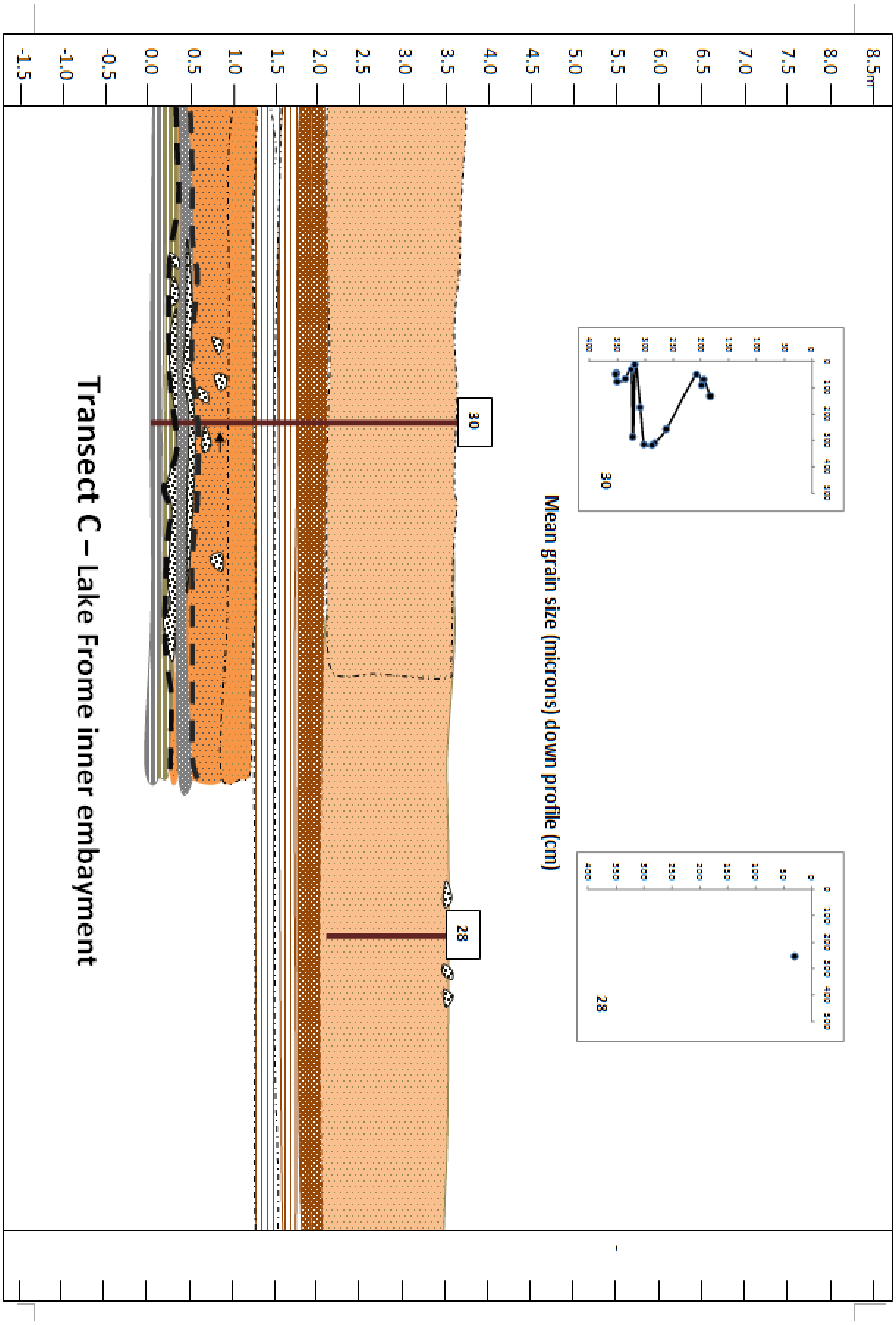


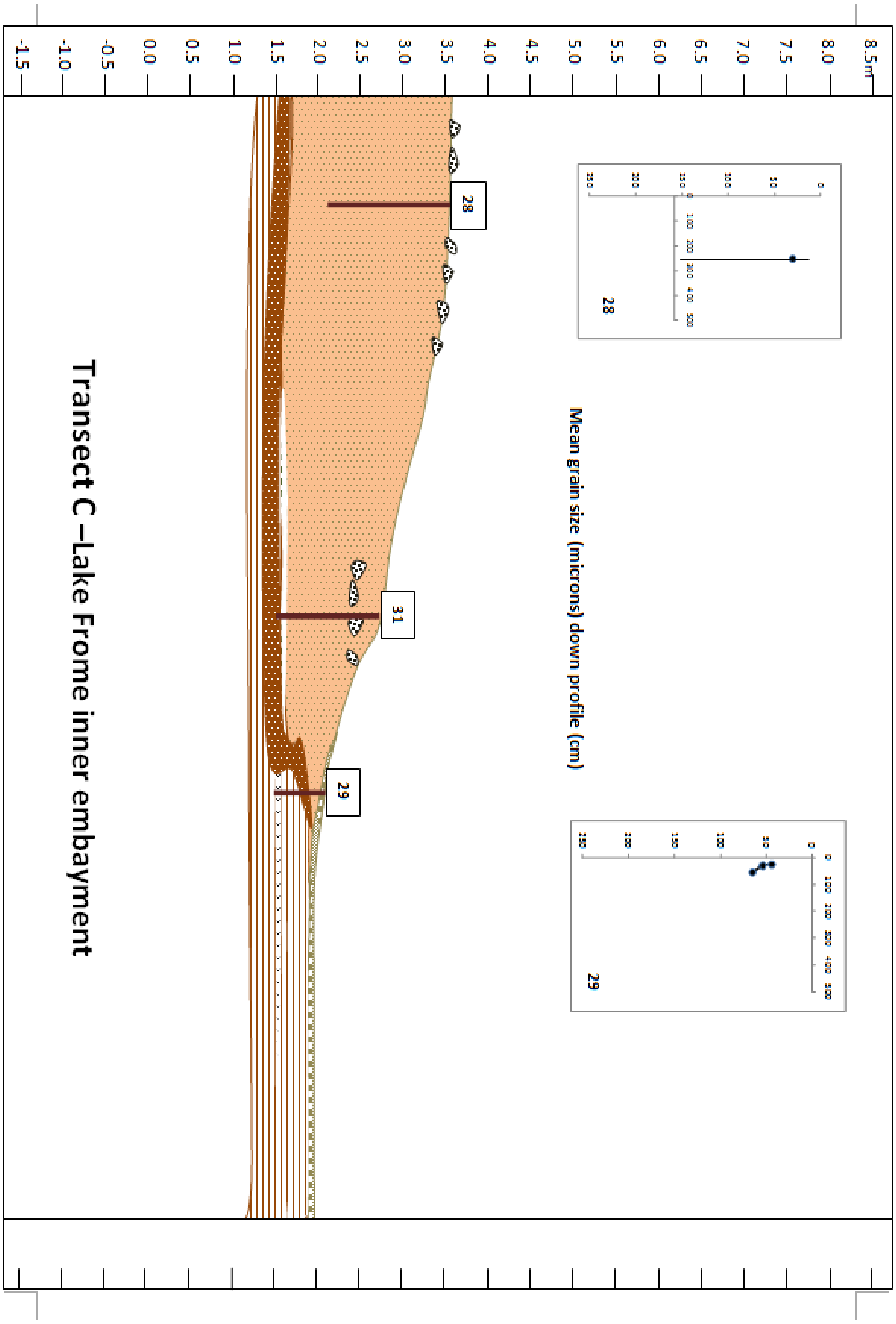
Transect B – Lake Frome long axis of palaeo-delta facies



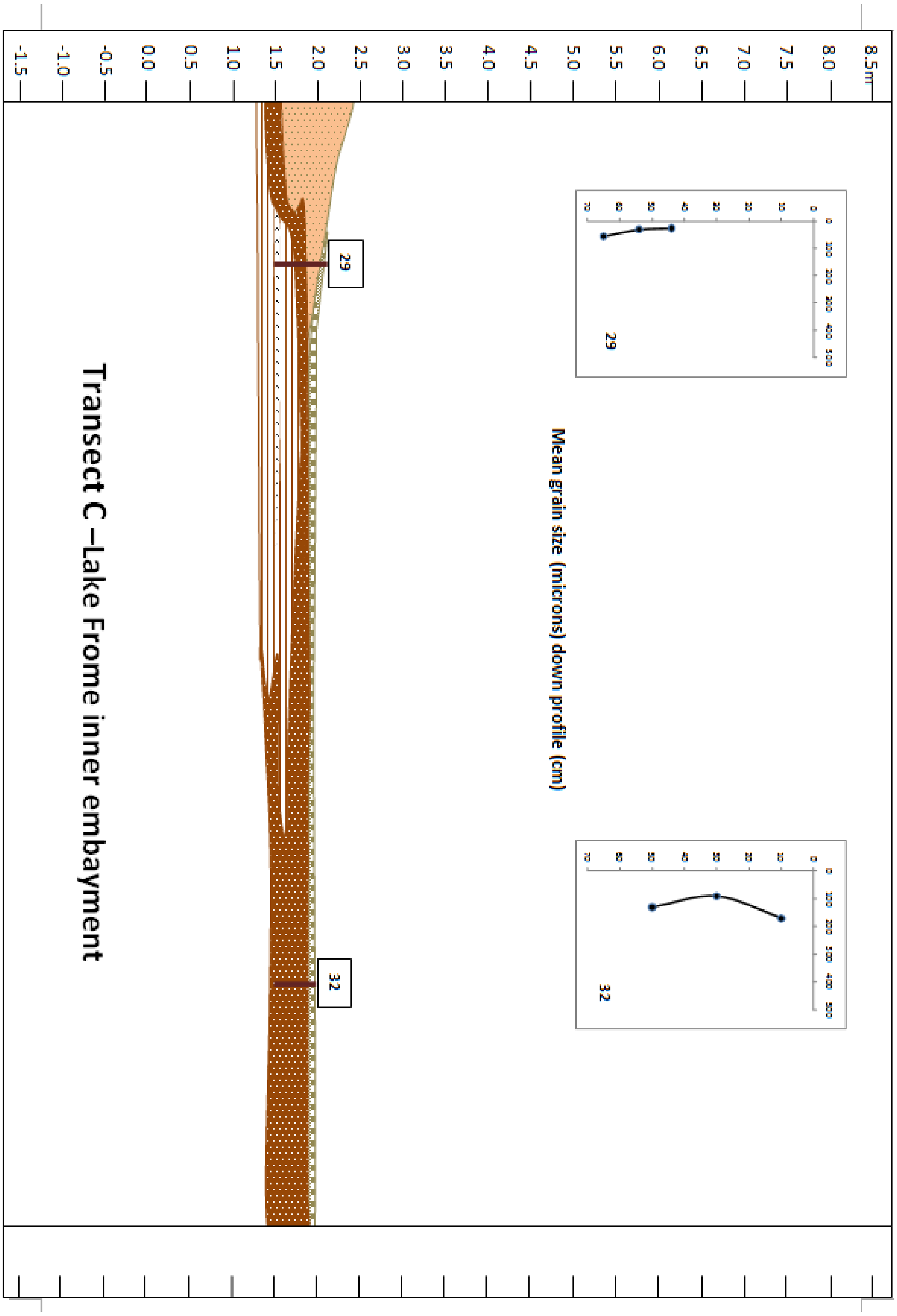
Transect B – Lake Frome long axis of palaeo-delta facies
Mean grain size (microns) down profile (cm)
22
20
21
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5m

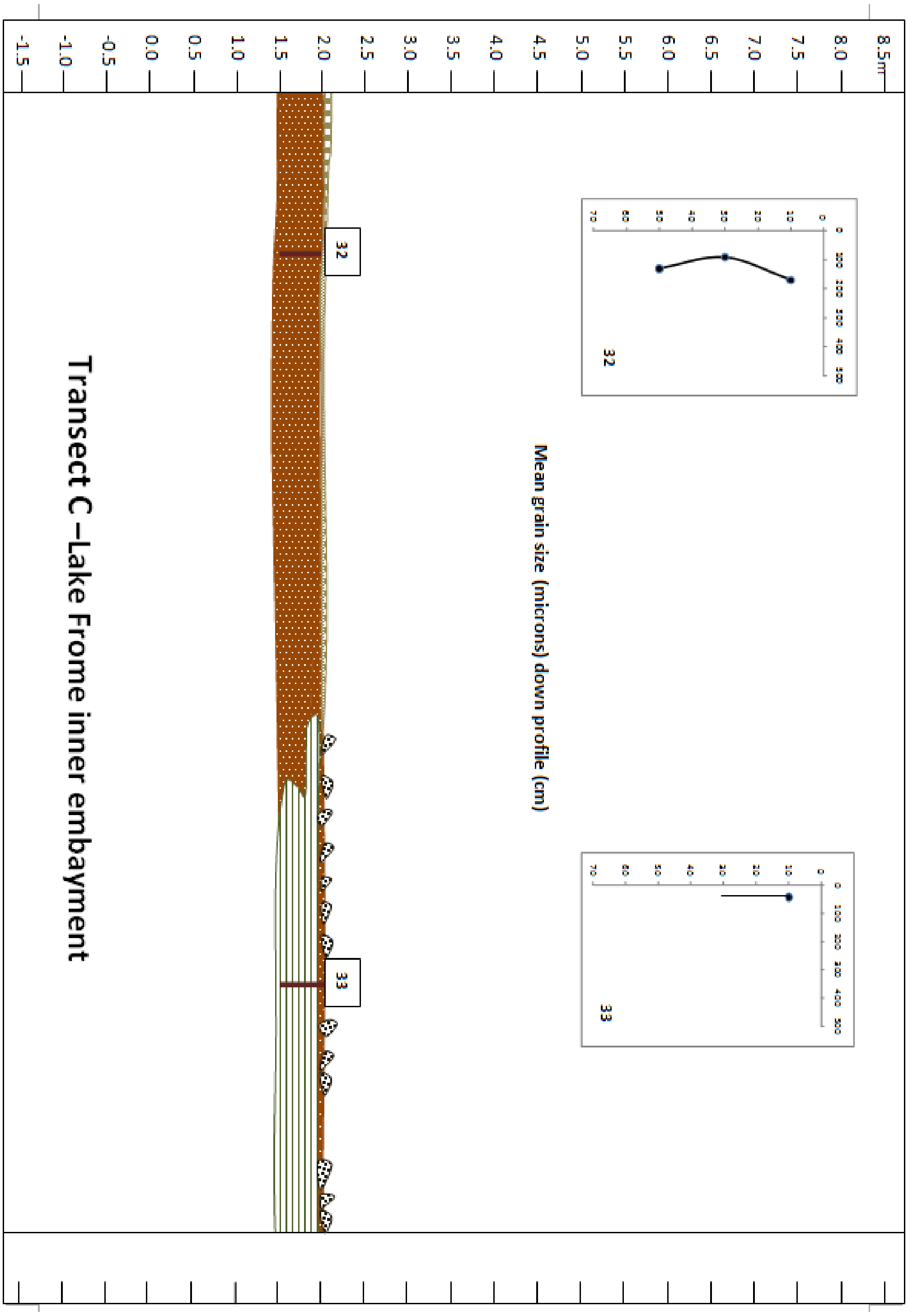
APPENDIX 4.9: TRANSECT C





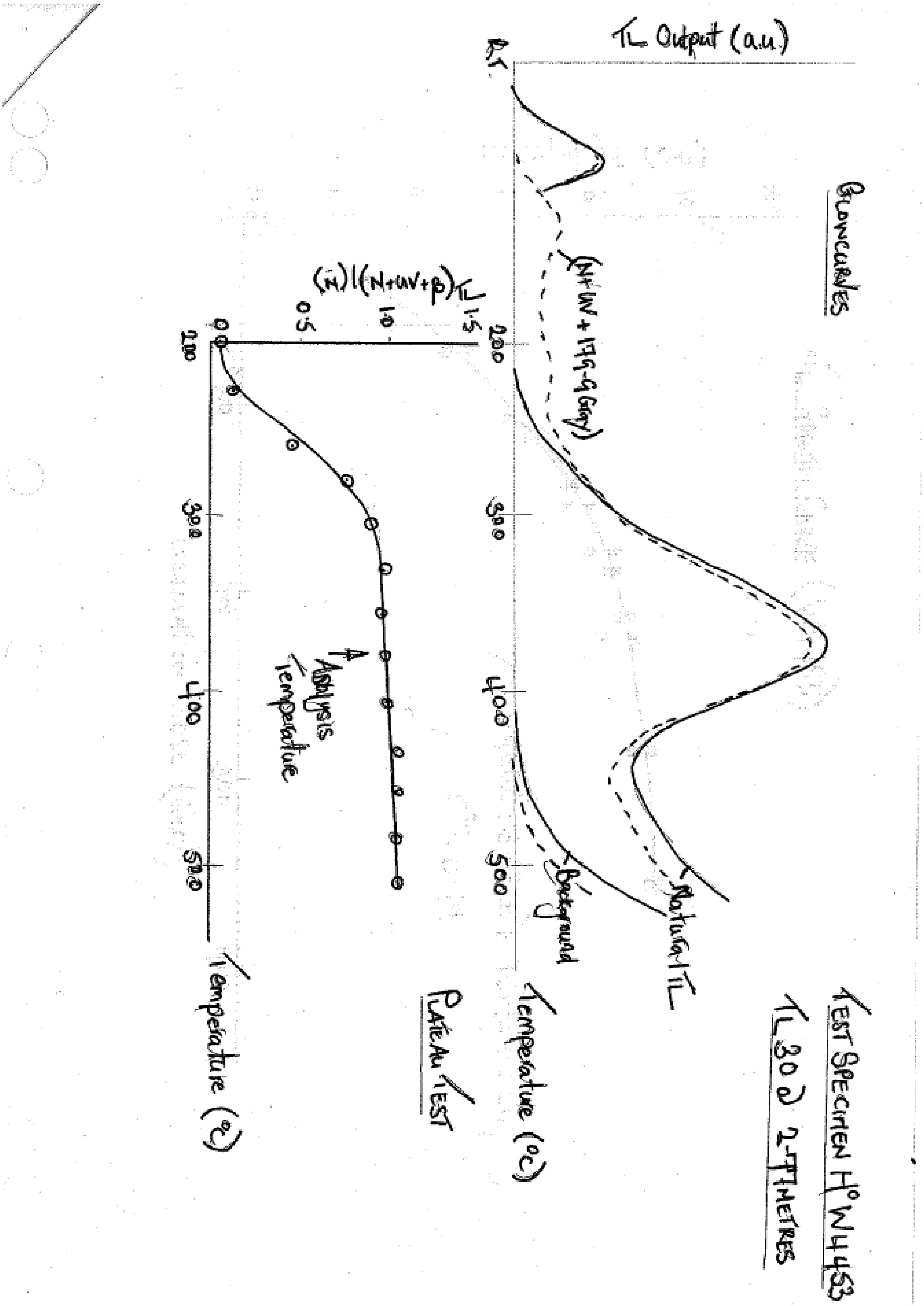
8.5m
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
28
31
29
Mean grain size (microns) down profile (cm)
Transect C –Lake Frome inner embayment


Transect C –Lake Frome inner embayment
Mean grain size (microns) down profile (cm)
29
32
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5m

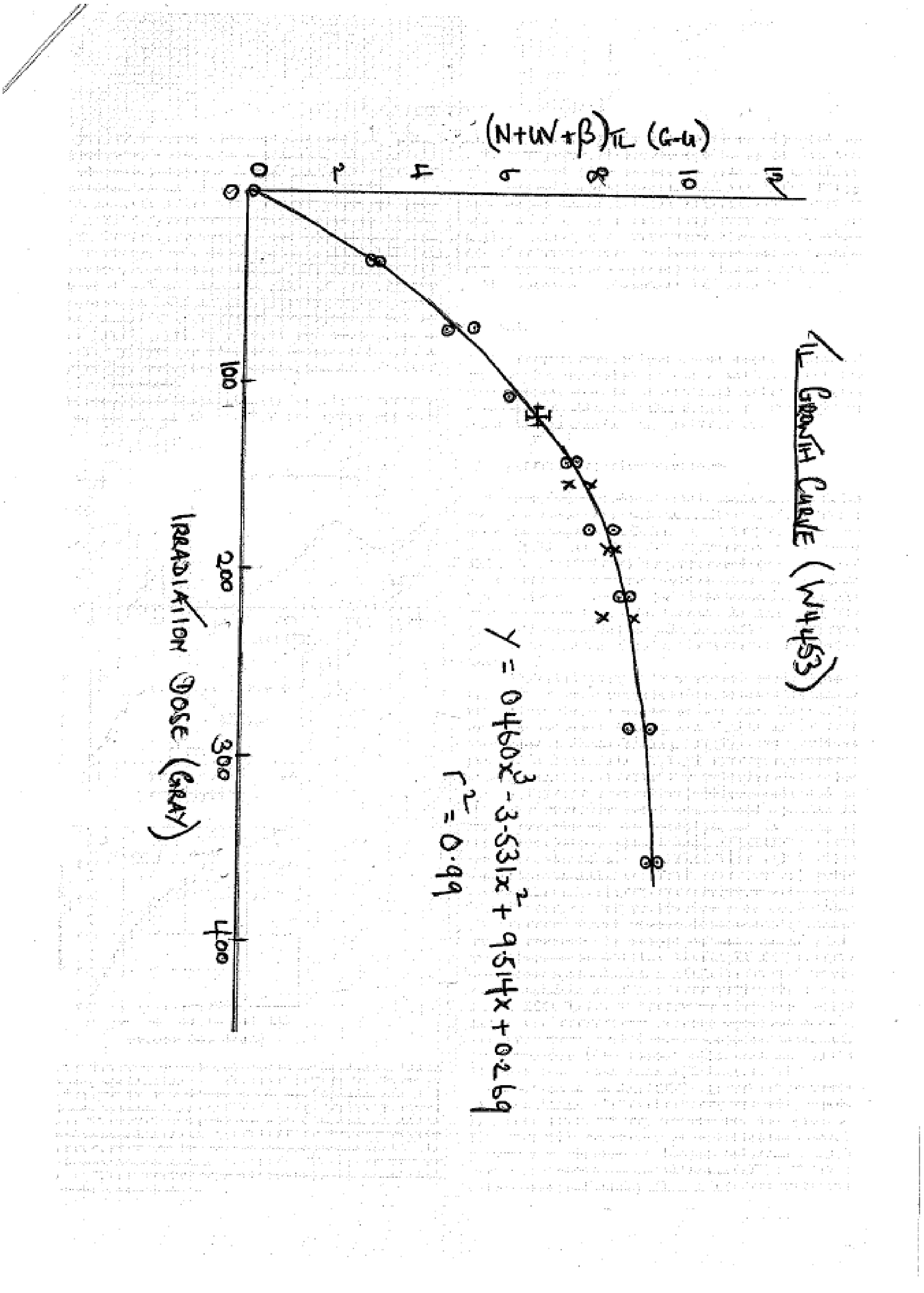


Transect C –Lake Frome inner embayment
Mean grain size (microns) down profile (cm)
32
33
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5m

APPENDIX 5.1 TL GLOWCURVE AND PLATEAU TEST W4453



APPENDIX 5.2 TL GROWTH CURVE W4453



APPENDIX 5.3 AMS 14C INFORMATION

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-25.6:lab. mult=1)

Laboratory number: **Beta-300466**

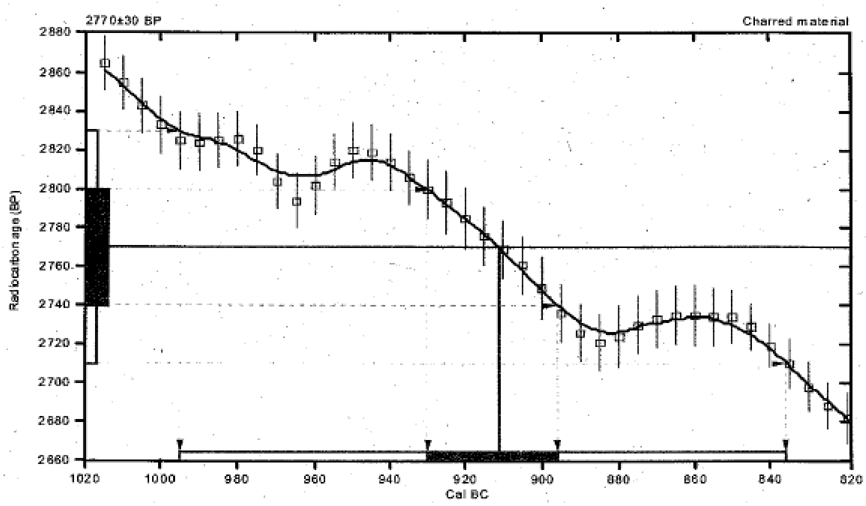
Conventional radiocarbon age: **2770±30 BP**

2 Sigma calibrated result: (95% probability) **Cal BC 1000 to 840 (Cal BP 2940 to 2790)**

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 910 (Cal BP 2860)

1 Sigma calibrated result: (68% probability) Cal BC 930 to 900 (Cal BP 2880 to 2850)



References:

Database used
INTCAL04
Calibration Database
INTCAL04 Radiocarbon Age Calibration
IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).
Mathematics
A Simplified Approach to Calibrating C14 Dates
Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Radiocarbon Dating Laboratory

4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • E-Mail: beta@radiocarbon.com

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APPENDIX 5.4 MICROFOSSIL CONTENT

Hole	Depth cm	Elevation (LHD)	Unit	Microfossils present	*Reticypris sp.* Numbers	*Diacypris dietzi* Numbers	*Diacypris whitei* Numbers	*Diacypris spinosa* Numbers	*Mytilocypr is sp.* Numbers	*Platycypri s baueri* Numbers
27	37	156	Active delta	Ostracoda	12	>25				10
3	19	186	Laminated	Ostracoda	-			1		
3	25	180	Laminated	Ostracoda	>30-40	6				
3	37	168	Laminated	Ostracoda	17	5				
3	42	163	Laminated	Ostracoda	>115-120	1				
3	50	155	Laminated	Ostracoda	>65-70	7				
3	58	147	Laminated	Ostracoda	>125-130	1			1	
3	63	142	Laminated	Ostracoda	>105-110	4		1	2	
3	100	105	Laminated	Ostracoda	>65-70				2	
18	20	180	Surface sands	Ostracoda	2					
18	40	160	Oxidised silt	-						
18	60	140	Oxidised silt	Ostracoda	17					
18	70	130	Oxidised silt	Ostracoda	11					
18	92	108	Laminated	Ostracoda	>85-90	1		4	3	
18	97	103	Laminated	Ostracoda	>35-40	1				
18	100	100	Laminated	Ostracoda	>75-80	30		1		
18	106	94	Laminated	Ostracoda	>100-105	2		6		
18	142	58	Laminated	Ostracoda	>30-35	1			1	
18	243	-43	Oxidised basal	-						
2	250	-47	Oxidised basal	-						
2	300	-97	Oxidised basal	Fish skeleton?						
13	585	60	Oxidised basal	-						
13	600	45	Reducing basal	Oogonia/Ostracoda	25-30	9	2	>120		

APPENDIX 5.5 AAR VALUES

Hole	Depth cm	Sample Number	UWGA code	Aspartic D/L	Glutamic D/L	Serine D/L
27	37	1	9362A	0.358	0.186	0.124
27	37	5	9362C	0.267	0.105	0.282
27	37	7	9362D	0.299	0.174	0.074
27	37	8	9371C	0.359	0.153	0.322
27	37	12	9371E	0.429	0.199	0.230
Mean				**0.342**	**0.163**	**0.206**
Std dev				**0.062**	**0.037**	**0.105**
3	25	4	9379D	0.453	0.345	0.167
3	25	7	9380B	0.385	0.298	0.132
3	25	8	9380C	0.398	0.346	0.119
3	25	9	9380D	0.384	0.303	0.141
3	25	11	9381A	0.466	0.427	0.141
3	25	12	9381B	0.397	0.275	0.125
3	25	15	9381E	0.495	0.419	0.147
3	25	19	9382D	0.485	0.409	0.122
3	25	22	9383B	0.354	0.258	0.179
Mean				**0.424**	**0.342**	**0.141**
Std dev				**0.051**	**0.064**	**0.020**
3	25	B1	9407A	0.480	0.461	0.171
3	25	B4	9407D	0.450	0.265	0.115
Mean						
Std dev						
3	42	2	9353B	0.468	0.433	0.111
3	42	3	9353C	0.493	0.456	0.168
3	42	4	9353D	0.477	0.418	0.158
3	42	6	9354A	0.489	0.476	0.129
3	42	9	9354D	0.413	0.388	0.110
3	42	12	9355B	0.515	0.394	0.139
3	42	13	9372A	0.380	0.272	0.095
3	42	14	9372B	0.581	0.371	0.141
3	42	18	9372C	0.465	0.345	0.154
3	42	21	9372D	0.503	0.415	0.170
3	42	23	9372E	0.424	0.358	0.125
3	42	24	9372F	0.411	0.353	0.163
Mean				**0.466**	**0.404**	**0.143**
Std dev				**0.036**	**0.042**	**0.022**
3	42	B1	9408A	0.472	0.299	0.107
3	42	B2	9408B	0.599	0.476	0.186
3	42	B3	9408C	0.460	0.409	0.118

Hole	Depth cm	Sample Number	UWGA code	Aspartic D/L	Glutamic D/L	Serine D/L
Std dev				**0.017**	**0.042**	**0.003**
3	50	7	9364B	0.401	0.301	0.205
3	50	8	9364C	0.482	0.424	0.154
3	50	10	9364E	0.407	0.343	0.165
3	50	11	9365A	0.433	0.391	0.283
3	50	13	9369A	0.567	0.474	0.206
Mean				**0.458**	**0.387**	**0.203**
Std dev				**0.069**	**0.068**	**0.051**
3	50	B25	9396A	0.406	0.288	0.124
3	50	B27	9396C	0.383	0.326	0.116
Mean				**0.395**	**0.307**	**0.120**
Std deviation				**0.016**	**0.027**	**0.006**
3	58	1	9356A	0.420	0.362	0.104
3	58	2	9356B	0.436	0.395	0.158
3	58	3	9356C	0.463	0.410	0.142
3	58	4	9356D	0.398	0.364	0.125
3	58	5	9356E	0.434	0.354	0.181
3	58	6	9357A	0.410	0.390	0.165
3	58	7	9357B	0.599	0.587	0.216
3	58	10	9357E	0.415	0.350	0.207
3	58	11	9358A	0.394	0.320	0.115
3	58	12	9358B	0.402	0.335	0.158
3	58	13	9373A	0.390	0.302	0.102
3	58	15	9373D	0.428	0.363	0.115
3	58	20	9374C	0.424	0.354	0.173
3	58	22	9374E	0.508	0.657	0.167
3	58	23	9375A	0.414	0.525	0.130
Mean				**0.420**	**0.363**	**0.149**
Std dev				**0.020**	**0.026**	**0.032**
3	63	5	9366E	0.434	0.402	0.121
3	63	8	9367C	0.440	0.365	0.123
3	63	11	9368A	0.409	0.408	0.123
3	63	12	9368B	0.428	0.344	0.102
3	63	14	9376B	0.435	0.372	0.147
3	63	16	9376D	0.461	0.387	0.117
3	63	19	9377B	0.506	0.417	0.136
3	63	22	9378A	0.438	0.354	0.120
3	63	23	9378B	0.415	0.389	0.128
3	63	24	9378C	0.458	0.441	0.213
Mean				**0.450**	**0.395**	**0.140**
Std dev				**0.029**	**0.029**	**0.034**

Hole	Depth cm	Sample Number	UWGA code	Aspartic D/L	Glutamic D/L	Serine D/L
3	100	7	9360B	0.428	0.306	0.144
3	100	11	9361A	0.412	0.342	0.130
3	100	16	9384C	0.384	0.282	0.103
3	100	18	9384E	0.480	0.462	0.152
3	100	22	9385D	0.399	0.306	0.113
3	100	23	9385E	0.381	0.295	0.102
Mean				**0.407**	**0.308**	**0.117**
Std dev				**0.020**	**0.022**	**0.022**
3	100	B25	9395A	0.420	0.326	0.102
3	100	B26	9395B	0.411	0.296	0.107
3	100	B29	9395E	0.391	0.304	0.131
Mean				**0.407**	**0.309**	**0.113**
Std dev				**0.015**	**0.016**	**0.016**
13	175	2	9397B	0.475	0.278	0.153
13	175	3	9397C	0.485	0.284	0.146
13	175	4	9397D	0.500	0.305	0.144
13	175	5	9397E	0.496	0.293	0.189
13	175	6	9398A	0.477	0.271	0.149
Mean				**0.487**	**0.286**	**0.156**
Std dev				**0.011**	**0.013**	**0.019**
13	175	B2	9399B	0.488	0.271	0.142
13	175	B3	9399C	0.598	0.384	0.204
13	175	B4	9399D	0.474	0.28	0.119
13	175	B5	9399E	0.502	0.316	0.155
13	175	B6	9400A	0.475	0.275	0.153
13	175	B7	9400B	0.523	0.378	0.181
13	175	B9	9400D	0.484	0.273	0.147
13	175	B10	9400E	0.559	0.344	0.138
Mean				**0.513**	**0.315**	**0.155**
Std dev				**0.045**	**0.048**	**0.026**
18	92	1	9409A	0.406	0.311	0.106
18	92	3	9409C	0.422	0.352	0.125
18	92	4	9409D	0.395	0.311	0.121
18	92	5	9409E	0.390	0.337	0.122
18	92	6	9409F	0.561	0.487	0.206
18	92	8	9410B	0.399	0.317	0.105
18	92	9	9410C	0.422	0.328	0.159
18	92	10	9410D	0.415	0.354	0.105
18	92	11	9410E	0.386	0.307	0.116
18	92	12	9410F	0.448	0.364	0.199
Mean				**0.409**	**0.331**	**0.129**
Std dev				**0.020**	**0.021**	**0.031**

Hole	Depth cm	Sample Number	UWGA code	Aspartic D/L	Glutamic D/L	Serine D/L
18	92	B4	9414D	0.390	0.259	0.101
Mean				**0.430**	**0.328**	**0.175**
Std dev				**0.006**	**0.003**	**0.001**
18	100	1	9405A	0.474	0.377	0.154
18	100	2	9405B	0.629	0.551	0.131
18	100	3	9405C	0.412	0.284	0.121
18	100	4	9405D	0.499	0.429	0.116
18	100	6	9406A	0.452	0.336	0.116
18	100	8	9406C	0.417	0.343	0.167
18	100	10	9406E	0.553	0.463	0.146
Mean				**0.468**	**0.372**	**0.137**
Std dev				**0.053**	**0.065**	**0.022**
18	100	B1	9423A	0.444	0.372	0.285
18	100	B3	9423B	0.407	0.358	0.143
18	100	B5	9423C	0.403	0.397	0.153
18	100	B6	9424A	0.458	0.386	0.181
18	100	B8	9424B	0.442	0.358	0.152
18	100	B9	9424C	0.465	0.434	0.160
Mean				**0.437**	**0.384**	**0.179**
Std dev				**0.026**	**0.029**	**0.053**
18	106	1	9403A	0.549	0.498	0.262
18	106	2	9403B	0.423	0.381	0.192
18	106	3	9403C	0.401	0.305	0.103
18	106	6	9404A	0.385	0.365	0.1
18	106	8	9404C	0.383	0.301	0.118
18	106	9	9404D	0.418	0.324	0.142
18	106	10	9404E	0.46	0.391	0.148
Mean				**0.412**	**0.345**	**0.134**
Std dev				**0.029**	**0.039**	**0.035**
18	106	B1	9411A	0.405	0.338	0.174
18	106	B3	9411C	0.517	0.471	0.157
18	106	B4	9411D	0.431	0.397	0.182
18	106	B5	9412A	0.467	0.403	0.174
18	106	B6	9412B	0.425	0.382	0.175
18	106	B7	9412C	0.402	0.344	0.144
Mean				**0.426**	**0.373**	**0.170**
Std dev				**0.026**	**0.030**	**0.015**
18	142	8	9413B	0.351	0.264	0.106
18	142	B2	9413C	0.458	0.414	0.157
18	142	B6	9413F	0.523	0.484	0.159
Mean				**0.491**	**0.449**	**0.158**
Std dev				**0.046**	**0.049**	**0.001**

Hole	Depth cm	Sample Number	UWGA code	Aspartic D/L	Glutamic D/L	Serine D/L
LE2 - 6	262	R2 7	9429C	0.487	0.202	0.216
LE2 - 6	262	R2 9	9429D	0.527	0.232	0.16
LE2 - 6	262	R2 14	9429D	0.531	0.242	0.353
LE2 - 6	262	R2 15	9430A	0.562	0.265	0.185
LE2 - 6	262	R2 17	9430B	0.527	0.245	0.112
LE2 - 6	262	R2 19	9430C	0.542	0.28	0.226
LE2 - 6	262	R2 21	9430D	0.539	0.258	0.136
Mean				**0.533**	**0.261**	**0.199**
Std dev				**0.041**	**0.041**	**0.069**
LE1 3	175	D1	9431A	0.527	0.265	0.123
LE1 3	175	D3	9431B	0.547	0.264	0.154
LE1 3	175	D5	9431C	0.541	0.254	0.14
LE1 3	175	D7	9431E	0.555	0.284	0.155
LE1 3	175	D9	9432A	0.561	0.293	0.129
LE1 3	175	D11	9432B	0.510	0.260	0.112
Mean				**0.540**	**0.270**	**0.136**
Std dev				**0.019**	**0.015**	**0.017**
LE2 6	262	D2	9433A	0.619	0.322	0.108
LE2 6	262	D10	9433B	0.650	0.391	0.143
LE2 6	262	D12	9433C	0.585	0.313	0.17
Mean				**0.618**	**0.342**	**0.140**
Std dev				**0.033**	**0.043**	**0.031**